17. *The* Shap Granite, *and the* Associated Igneous *and* Metamorphic Rocks.

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[Plates X., XI., & XII.]

§ I. Introduction.

Having been struck with the absence of any detailed description of the metamorphism caused by the intrusion of a granite mass into a complex group of volcanic products, we devoted ourselves to an examination of the alteration produced by the well-known intrusion of Shap Fell in Westmorland, being led thereto by a knowledge that the volcanic rocks themselves presented a considerable diversity of characters, and that we should be to a certain extent able to contrast the effects produced on the volcanic rocks with those shown by fairly normal sedimentary rocks of various kinds. Although the intrusive mass has been so frequently noticed, and the literature on the subject is somewhat extensive, very few authors have touched in detail upon the composition of the granite and on the metamorphism of the surrounding rocks. Indeed, the following papers are all to which we shall have to refer with any frequency, and which we therefore, to save trouble, cite at the outset:—

Prof. H. A. Nicholson, "On the Granite of Shap in Westmoreland." Trans. Edin. Geol. Soc. vol. i. (1868) p. 133.

J. Clifton Ward, "On the Granitic, Granitoid, and Associated Metamorphic Rocks of the Lake District.—Part II. On the Eskdale and Shap Granites, with their Associated Metamorphic Rocks." Quart. Journ. Geol. Soc. vol. xxxi. (1875) p. 590.

Professors Harkness and Nicholson, "On the Strata and their Fossil Contents between the Borrowdale Series of the North of England and the Coniston Flags." Quart. Journ. Geol. Soc. vol. xxxiii. (1877) p. 461.

J. A. Phillips, "On Concretionary Patches and Fragments of other Rocks contained in Granite." Quart. Journ. Geol. Soc. vol. xxxvi. (1880) p. 1.

J. A. Phillips, "Additional Note on Certain Inclusions in Granites." Quart. Journ. Geol. Soc. vol. xxxviii. (1882) p. 216.

J. J. H. Teall, "British Petrography" (1888), p. 322.
Messrs. Aveline, Hughes, and Strahan, Mem. Geol. Survey, "The Geology of the Country around Kendal, Sedbergh, Bowness, and Tebay," 2nd ed. (1888) p. 34.

The granite forms an irregular oval, having a longer diameter from E. to W. of a little under two miles, whilst its shorter diameter in a N. and S. direction is somewhat more than a mile, and the intrusion is situated very near to the boundary-line between the Ordovician and Silurian rocks, both of which are altered by it, and, as will be subsequently seen, its probable apophyses penetrate upwards into rocks of Lower Ludlow age. On the other hand, it was long ago pointed out that the porphyritic pink felspars of the granite occur as fragments in the basal conglomerate which underlies the Carboniferous Limestone. As they appear to be somewhat limited therein, we may mention that they are seen in vast profusion in a small cliff on the right bank of Wasdale Beck, a few yards S.W. of Shap Wells Hotel, and near to where the Carboniferous conglomerate rests upon the upturned edges of the Coniston Flags. The date of intrusion of the granite is therefore definitely fixed as taking place after the deposition of the Lower Ludlow rocks, and before that of the basal Carboniferous conglomerate, and it is usually assumed that the rock was intruded in post-Silurian but pre-Carboniferous times, as is indeed highly probable. The apophyses of the granite occur in a considerable abundance to the south, as seen on the Geol. Survey map, and there are a good number on the north side also. Besides this, there is a network of irregular veins and branches along the immediate margin, especially on the steep west face, which renders the determination of the actual boundary somewhat difficult, and indeed the linear boundary of the map must be taken as drawn through the points where the granite is not mixed up to any extent with portions of the rock through which it has broken*. The general shape of the intrusive mass will be discussed subsequently.

The metamorphism produced by the granite is stated in the Survey Memoir to extend to a distance of about a mile from the margin. This appears to be the case, though we find that the production of new materials is confined to a belt extending not more than $\frac{3}{4}$ mile from the contact.

It is necessary here to give some account of the trend, order of succession, and lithological characters of the various rocks which come within the influence of the granitic mass, and to describe a section showing the succession of such rocks where they put on their normal aspect away from the granite.

The principal lithological varieties of the rock are exhibited upon the map, but for our purpose a more minute subdivision than can be laid down upon a small map is necessary, and we therefore

* [We have corrected the northern boundary of the granite on our map by reference to the MS. six-inch map in the Geological Survey Office, to which the Director-General has kindly allowed us access.—March 11th, 1891.]

append the following table of succession of the rocks in descending order:—

Bannisdale Slates.	
Coniston Grits.	
Coniston Flags,	Upper Coldwell Beds. Middle do. do. Lower do. do. Brathay Flags.
Stockdale Shales (missing).	
Ashgill Shales (missing).	
Coniston Limestone,	Upper Limestone. Calcareous Breccia. Rhyolite. Lower (Stile End) Limestone.
Upper part of "Borrowdale Series" of Harkness and Nicholson	Rhyolitic Group. Andesitic Group.

All of these are affected by the granite with the exception of the Bannisdale Slates, into which, however, apophyses of the granite are intruded.

It will be convenient if we append a short description of the general characters of the rocks, as seen in a fairly continuous section at no great distance from the granite, but nevertheless outside the zone of alteration, noticing at the same time any marked differences (not due to metamorphism) between the rocks in this section and those developed within the altered region.

Fortunately, an excellent section of the strata (fig. 1, p. 270) is shown in Stockdale, at a distance of less than four miles from the S.W. margin of the granite, and the strata can be traced more or less continuously from that valley to the margin of the granite, disposing of all doubts as to the identity of the different beds.

Commencing with the Silurian rocks, and omitting the Bannisdale Slates, we find the Coniston Grits in Long Sleddale, half a mile below Stockdale, in their normal form of fine-grained grauwacke grits, striking with the rest of the Silurian rocks of this tract in a general E.N.E.–W.S.W. direction. Below them are the Upper Coniston Flags (Upper Coldwell Beds), slightly gritty laminated flags of a bluish colour. The Middle Coldwell Beds differ from these in being calcareous, whilst the Lower Coldwell Beds are grits very similar in character to the beds of the Coniston Grits. All of these beds, except the latter, contain Ludlow fossils, and the Lower Coldwell grits probably mark the base of that series.

The Lower Coniston Flags (Brathay Flags), the equivalents of the Wenlock series, and containing the usual Wenlock graptolites, are blue laminated flags, less gritty than the beds of the Upper Flag division, but otherwise resembling them.

The Stockdale Shales, being faulted out in the zone of alteration, do not require description.

The Upper Limestone of the Coniston Limestone series is an impure limestone, containing much argillaceous matter, and interstratified with calcareous shales which contain a certain amount of fine ashy material. Its lower part is more calcareous than the

upper, but is by no means pure. At its base is a breccia, which is somewhat variable, consisting of a calcareous ashy matrix with rounded and angular fragments of rhyolite. The upper part of this breccia consists of a limestone with a few more or less rounded rhyolite fragments, whilst the base is to a large extent composed of rhyolitic detritus with comparatively little calcareous matter. This breccia is seen occupying precisely the same position at Yarlside Crag, again at a point $\frac{5}{6}$ mile W.S.W. of Wasdale Head Farm, immediately west of the farm itself, and in Blea Beck, at the Spa Well in the grounds of Shap Wells Hotel. Below this is a thin ash band, and then a thick rhyolite, nodular at the summit and fissile below. This is well known, being inserted on the Survey Map from Wasdale Head Farm to Stile End, on the west side of Long Sleddale, a total distance of over five miles, and it is the rock which is figured in Mr. Teall's "British Petrography," plate xxxviii., the specimen figured having been obtained from a point half a mile W. of Stockdale.

The Lower Limestone (Stile End Limestone) is less calcareous and more ashy than the upper one, and the calcareous matter is often collected into nodules.

The Rhyolitic Group below the Coniston Limestone, and forming here the summit of the Borrowdale series, consists of a succession of fine green rhyolitic ashes and breccias of no great coarseness, the latter containing rhyolitic fragments *. It will be eventually seen that farther to the west this group also contains rhyolite flows, and beds of a gritty character, which are not found in the present section, but fortunately their nature is readily recognizable even within the zone of alteration.

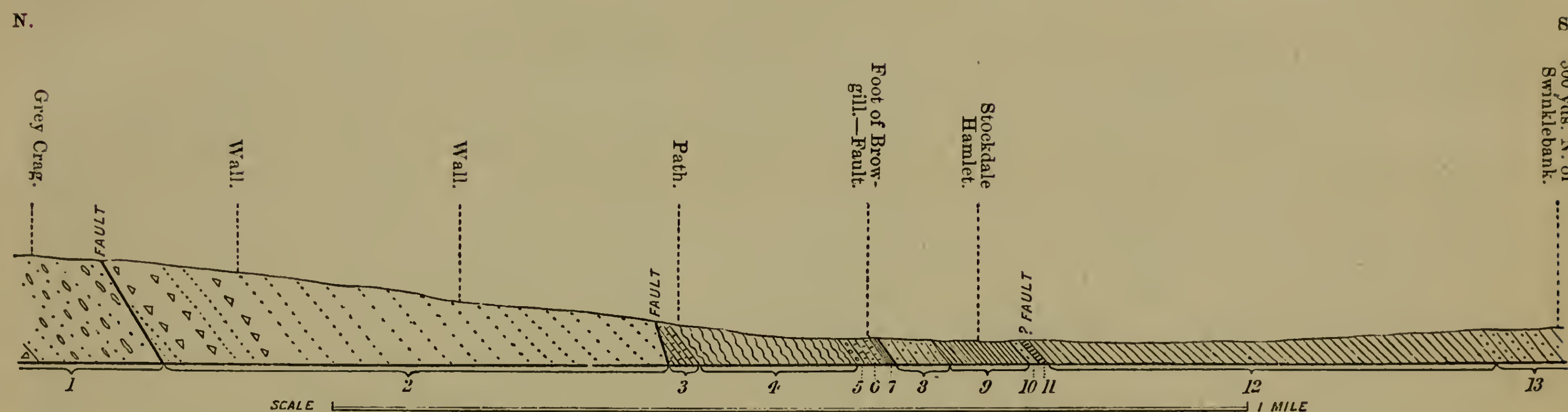
Lastly, below Grey Crag we meet with a group of vesicular andesites, interstratified with darker ashes, and with some breccias, the latter containing rhyolitic fragments, as is usually the case throughout the whole Borrowdale series whatsoever may be the nature of the associated lavas. These andesites have evidently undergone "weathering" at an early period, as their vesicles are now filled with calcite, chlorite, or both, and when the rocks have been subjected to cleavage, the vesicles have been flattened along the cleavage-planes.

In order to show the fairly constant character of the rocks above described, it will be convenient to give details of two other sections, one near the granite, and the other somewhat more remote, though still within the zone of alteration.

The section (fig. 2, p. 271) is taken obliquely across the strike of the beds (which has here curved round somewhat in a manner to be described in the sequel), being drawn from Demings Moss, about $\frac{1}{2}$ mile S. of the granite margin, to Wasdale Pike. The Coniston Grits are seen at Demings Moss, and the Upper Coldwell Beds extend from here to the summit of Packhouse Hill, in a somewhat

* In figs. 1–3, amongst the volcanic rocks, the wrinkled lines indicate rhyolite flows, the oval markings andesite flows, whilst rhyolitic and andesitic ashes are indicated by fine dots, and breccias by triangles.

Fig. 1.—*Section down Stockdale Beck, continued towards Swinklebank.*



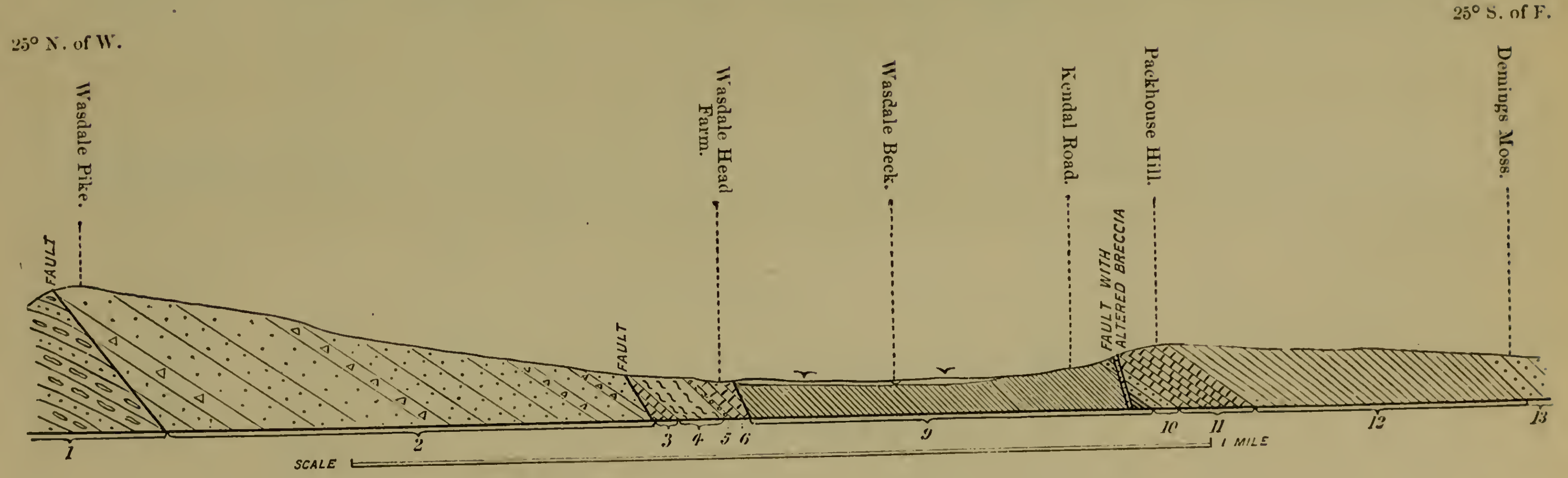
13. Coniston Grits.
12. Upper Coldwell Beds. } Coniston Flags.
11. Middle Coldwell Beds.
10. Lower Coldwell Beds.
9. Brathay Flags.

8. Browgill Beds. } Stockdale Shales.
7. Skellgill Beds.

6. Upper Coniston Limestone. } Coniston Limestone series.
5. Calcareous Breccia.
4. Rhyolite.
3. Lower Coniston (Stile End) Limestone.

2. Rhyolitic ashes and breccias. } Part of Borrowdale series.
1. Andesites, andesitic ashes, and breccias.

Fig. 2.—*Section from Wasdale Pike to Demings Moss, across the metamorphosed beds.*



13. Coniston Grits.
12. Upper Coldwell Beds.
11. Middle Coldwell Beds.
10. Lower Coldwell Beds.
9. Brathay Flags.

} Coniston Flags. (12–9)

6. Upper Coniston Limestone.
5. Calcareous Breccia.
4. Rhyolite.
3. Lower Coniston (Stile End) Limestone.

} Coniston Limestone series.

2. Rhyolitic ashes and breccias.
1. Andesites, andesitic ashes, and breccias.

} Part of Borrowdale series.

Alluvium.

"porcellanized" condition; they are lighter than in the unaltered state, and break with a conchoidal fracture, but the planes of lamination are clearly shown. The Middle Coldwell Beds occur as white or cream-coloured laminated porcellanous beds on the summit of Packhouse Hill, and immediately below them, above the road from Kendal to Shap, the Lower Coldwell Beds crop out as quartzite, though there is a fault between the Middle and Lower Coldwell Beds marked by a breccia composed of fragments of the two rocks, and itself altered by the granite. These are in turn underlain by the Brathay Flags, which strongly resemble the Upper Coldwell Beds in general appearance, though they have undergone greater alteration.

On the north side of Wasdale Beck the Upper Limestone band of the Coniston Limestone occurs in a small stream coming from the north, immediately west of Wasdale Head Farm. It is greatly altered but clearly recognizable, though changed into a white saccharoidal rock, for it has more finely-laminated beds interstratified with it, and at its base passes into the breccia with fragments of rhyolite seen weathering out on the exposed surfaces. Beneath this the rhyolite is readily recognizable, nodular at the summit, and fissile below, and underneath this comes the Lower Limestone, with the original calcareous patches occurring as white nodular masses embedded in a less pure rock. The presence of the Coniston Limestone at this point was recognized by Profs. Harkness and Nicholson so long ago as 1868 *.

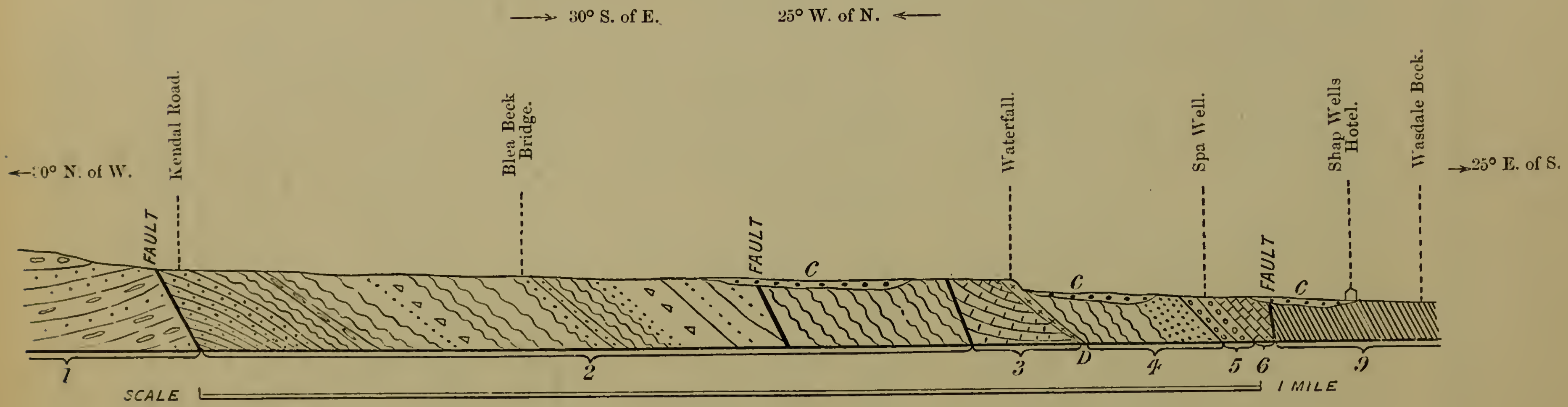
Ascending the hill from this point, a series of rhyolitic ashes and agglomerates in a state of considerable alteration is traversed until the summit of Wasdale Pike is reached, and immediately north of this the vesicular andesites and interbedded banded ashes crop out on the moorlands between this point and Sleddale Pike. We may here state that we assume the presence of vesicles to be sufficient evidence that the rocks in which they occur are true lavas and not ashes, as we cannot conceive the production of vesicles of this nature throughout the whole mass of a fragmental accumulation, and the microscope fully confirms our view. In this manner we are often enabled to distinguish between lavas and ashes even when the rocks have undergone great change near the contact with the granite.

The third section (fig. 3) is drawn from the Coniston Flags of Wasdale Beck, through the grounds of Shap Wells Hotel, in a direction generally parallel with the course of Blea Beck to the Andesitic Group west of the high road, on the southern flanks of Low Fell (Tewsett Pike).

The Brathay Flags are here hardened and splintery, and of a dark colour; they contain graptolites allied to *Monograptus vomerinus*. Between Wasdale Beck and the Spa Well in Blea Beck the lower rocks are covered by red conglomerate, but there is not sufficient room in the interval for the Stockdale Shales, the Ashgill

* Quart. Journ. Geol. Soc. vol. xxiv. p. 296.

Fig. 3.—*Section along Blea Beck from S. slope of Tewsett Pike to Shap Wells Hotel.*



c. Carboniferous Conglomerate.
D. Dyke.
9. Brathay Flags.—Part of Coniston Flags.

6. Upper Coniston Limestone.
5. Calcareous Breccia.
4. Rhyolite.
3. Lower Coniston (Stile End) Limestone.
} Coniston Limestone series.

2. Rhyolites, rhyolitic ashes, and breccias.
1. Andesites and andesitic ashes.
} Part of Borrowdale series.

Shales, and the higher portions of the Upper Limestone. The lower part of the latter at the Spa Well consists of 15 feet of nodular limestone, and banded limestones in calcareous shales, all somewhat hardened, but not greatly metamorphosed. It passes down into the breccia, which is very calcareous in its upper six feet, and crowded with small fragments of rhyolite, whilst the lower thirty feet consists of calcareous shales and grits with few rhyolite-fragments. The lower part of the breccia contains casts of *Lindstrœmia* and fragments of large trilobites in places, whilst a thin grit associated with it yields numerous *Tentaculites*. After a short interval, 10 feet of flaky rhyolitic ash is seen dipping down stream at a low angle, and then a break of many yards is occupied by the red conglomerate. At the top of the Hotel Plantation is a claret-coloured felsite with quartz crystals and tolerably large porphyritic felspars. Although this is in the position of the rhyolite between the two limestones in Stockdale and elsewhere, we have satisfied ourselves that it is intrusive. There is considerable disturbance at the junction between it and the underlying limestone, which is about sixty feet thick, and consists of calcareous bands and nodules interstratified with more shaly beds.

The top of the Rhyolitic Group is a nodular rhyolite, and, after another interval occupied by Carboniferous conglomerate, we meet with an alternation of more or less altered rhyolitic ashes, breccias, and lava flows, and one thin andesite, which extend up Blea Beck to the W. side of the high road, where they are faulted against the vesicular andesites and banded ashes of the south side of Tewsett Pike.

Hitherto we have merely considered the general succession of the beds without reference to their changes of strike and the faults by which they are affected, and it remains to say a few words concerning these.

The normal E.N.E.–W.S.W. strike of the Silurian strata and of the Coniston Limestone Group is slightly changed in the vicinity of the granite, curving round its southern margin. The Rhyolitic Group has its strike more strongly deflected, for the rocks turn somewhat sharply towards the S.E. on the western side of the granite, and appear to curve round with a mean N.E.–S.W. strike on the eastern side. The andesites dip at first in a southerly direction on the S.W. margin of the granite, though farther north they appear to turn over, and maintain a general northerly dip all along the northern margin of the granite; so that on the N.E. margin, the Andesitic Group is seen dipping away from the junction of the Andesitic and Rhyolitic Groups, as represented on the map. The absence of the Stockdale Shales indicates the existence of a strike-fault running between the Coniston Flag and Coniston Limestone series. This fault has been recently described by one of us, in a joint paper with Prof. Nicholson, as running across the district *.

* See Quart. Journ. Geol. Soc. vol. xliv. (1888) pp. 662 *et seqq.*

A second fault occurs at the base of the Stile End Limestone, as shown by its attenuation in Stockdale and its disappearance elsewhere; also by the change of strike in the Rhyolitic Group below the Stile End Limestone of Blea Beck.

Another fault separates the Rhyolitic Group from the Andesitic rocks to the north of it. The proof of this is furnished by the difference of dip of the two groups on the north-east margin of the granite, where the south limb of the anticline in the Andesitic Group is entirely cut out.

Besides these faults, others of minor importance cut through the Rhyolitic Group to the east of the granite. Their general position is shown on the map, though, owing to the quantity of drift which here covers the ground, we have not been able, in all cases, to indicate their exact position.

[As the existence of these minor faults does not directly bear upon the subject of this paper, we have not fully discussed the evidence for their general trend and hades. We hope to recur to this, however, in a future communication.—March 11th, 1891.]

§ II. Description of the Granite.

The well-known "Shap Granite" is familiar, not only as an ornamental building-stone, but also as the material of the famous boulders which have so often been made use of in tracing lines of glaciation in the north of England. The most striking feature of the rock is the occurrence of flesh-coloured crystals of felspar, one or two inches in length, in a matrix of moderately coarse texture and usually of greyish hue. In this matrix orthoclase, quartz, biotite, and a striated felspar may be detected by the unassisted eye or with a lens.

In strict accuracy the name "granite" is not quite applicable to the rock, which is differentiated from typical granitic rocks by its porphyritic character; but the name "granite-porphyry" has not been applied in this country except to rocks with a matrix of very fine texture, and it will be sufficient to designate the Shap Fell rock by its popular title, "porphyritic granite." We shall see, however, that its micro-structure also presents a departure from the rules which hold in most granitic rocks, the quartz being of anterior consolidation to the orthoclase.

The preponderance of felspars in the rock is partly explained by its chemical composition, the silica-percentage being rather low. Mr. E. J. Garwood, who has kindly made several analyses for us, finds 69·78, and Dr. J. B. Cohen, in another specimen, 68·55 per cent. of SiO_2. The rock is thus less acid than the Skiddaw and Eskdale granites, which yield 75·223 and 73·573 per cent. of silica respectively. Dr. Cohen's analysis is given on the next page (mean of two):—

	I.	II.
SiO_2	68·55	68·54
Al_2O_3	16·21	15·82
Fe_2O_3	2·26	2·26
FeO	not estimated	—
MnO	0·45	0·52
MgO	1·04	0·93
CaO	2·40	1·99
Na_2O	4·08	4·23
K_2O	4·14	4·45
H_2O	not estimated	not estimated
	99·13	98·74

I. Shap-Fell granite, bulk-analysis from an average specimen weighing 10 lb.; anal. J. B. Cohen.

II. Calculated composition obtained from the analyses of the porphyritic felspars and the groundmass given below (p. 278), on the supposition of one part of porphyritic crystals to nine of groundmass.

The specific gravity of a specimen of the "light" Shap granite was found to be 2·687.

The microscope reveals several minerals in addition to those enumerated above *.

Apatite is present in all the slides examined. It occurs in little prisms with hexagonal cross-section, and sometimes in very slender needles.

Zircon, in small quantity, is also a constant constituent, forming small prisms terminated by an obtuse pyramid. These two minerals are always the earliest products of consolidation, and contain no inclusions.

Magnetite is usually present, in little octahedra, in clusters of partly-developed crystals, or in less regular patches. The bulk of the mineral has separated at an early stage, but sometimes a portion is seen to mould the mica and later minerals.

Sphene is always present and often abundant. It commonly shows good crystal forms; namely, n (123), c (001), and y (101), in Miller's notation; but twinning is not met with. The cleavage-traces are often apparent, making acute angles with the bounding lines of the section. The colour in thin sections is light to moderately deep brown, with well-marked pleochroism. Longitudinal sections show the three forms mentioned, n being the best-developed; one of the axes of elasticity (α) is nearly parallel to the length of such a section, and vibrations in this direction give a pale straw colour, in the perpendicular direction a light reddish brown. Transverse sections are parallelograms bounded by n-faces only, and show a deeper colour than the others, with slightly less dichroism. The absorption formula is—

$$\gamma > \beta > \alpha.$$

* The specimens illustrating this paper, with about 150 slides, are in the Woodwardian Museum at Cambridge. The figures given in square brackets refer to the numbers of the slides.

Looking at Lane's * two types of rock-forming sphene, it appears that this corresponds to the type which he associates with rocks poor in alkalies and rich in magnesia and iron-oxides. The sphene in our rock is free from inclusions, excepting occasional crystals of zircon and magnetite. The mineral sometimes occurs in granular patches, but there is no reason to doubt that these also are of original formation.

Dark mica is the only ferro-magnesian silicate proper to the rock. It forms moderately small flakes, which almost always, when well bounded, show the pseudo-hexagonal appearance with large basal plane. In connexion with certain marginal modifications of the rock, however, there occur larger plates of mica with a different habit. These have the shape of long narrow blades, bounded apparently by the forms *c* (001) and *b* (010), with irregular terminations. They are often as much as an inch long, with a breadth of less than $\frac{1}{10}$ inch. When fresh, the mica is of a deep brown colour with intense pleochroism, vibrations perpendicular to the α-axis (*i. e.* nearly parallel to the cleavage-traces in a section) being absorbed almost to opaqueness. The bisectrix is not quite perpendicular to the basal plane, as may be verified by a slightly oblique extinction in sections. This also enables us to detect in some crystals a lamellar twinning parallel to the base.

The mica encloses occasionally any of the previously-named constituents, besides its own secondary products. Its most usual mode of alteration, exhibited in almost all the slides, results in a partial decoloration, or more frequently a green colour in place of the brown, and a considerable diminution in the absorption and pleochroism. The process is effected along the cleavage-planes of the mica, and often gives rise to irregular lamellæ of green colour alternating with the brown †. A separation of granular magnetite invariably accompanies this mode of decomposition. Side by side with flakes so affected there are often others converted in their interior into a reddish-brown substance free from magnetite. This shows less intense pleochroism than the fresh mica, the absorption being rather less parallel to the β and γ axes, and greater parallel to α. The optical properties are retained so far as to show the lamellar twinning between crossed nicols, but the cleavage is obliterated. Probably this represents a further stage of change than the green mineral, the secondary magnetite having been reabsorbed in the form of ferric oxide. The marginal parts of the flakes so affected are usually green, and still show cleavage-traces in the sections. An examination of some basal sections of mica in the slides, or, better, of thin films carefully flaked off from the mineral, frequently reveals numerous minute needles of rutile disposed in three directions parallel to the boundaries of the hexagon. These we have met with only in the decomposing mica, and they may possibly be secondary

* Tscherm. Min. u. Petr. Mitth. (N.S.) vol. ix. (1888) p. 207.
† See Teall's 'British Petrography' (1888), pl. xxxv. fig. 1.

products rather than original inclusions *. They are well seen in the blade-like micas already referred to.

Mr. J. A. Phillips mentioned hornblende as a constituent of the Shap granite, but it is not found in any of our numerous specimens and slices.

The felspars of our rock fall under three heads: the earlier orthoclase, the plagioclase, and the later orthoclase. The first builds the large red crystals which give to the rock its porphyritic appearance. The crystals show the common habit, and are usually twinned on the Carlsbad law. The mineral is clearly monoclinic. Mr. Phillips speaks of it in one place as "microcline," but as the specimens alluded to formed part of the façade of a building, it is clear that they could not have been subjected to any decisive test. These large felspars enclose crystals of apatite and sphene, besides occasional flakes of mica and prisms of striated plagioclase. More rarely they contain little patches of quartz, or even a well-bounded crystal of that mineral [395]. Sometimes, however, we find numerous round grains of quartz enclosed in the marginal portion of the felspar crystals [796]. The inference is that these porphyritic crystals were formed at a time when the accessory constituents of the rock had already separated out, and the mica and plagioclase had begun to form, and that their growth only occasionally continued into the stage at which free silica began to separate.

For the following analysis (I.) of the porphyritic felspars we are indebted to the kindness of Dr. J. B. Cohen. The figures are the mean of two determinations :—

	I.	II.	III.
SiO_2	65·41	64·48	68·89
Al_2O_3	18·97	19·04	15·48
Fe_2O_3	..	..	2·46
FeO	0·51	..	traces
MnO	traces	..	0·58
MgO	0·01	1·02	1·04
CaO	0·73	..	2·13
Na_2O	2·15	2·64	4·69
K_2O	11·23	10·74	3·70
H_2O	not estim.	0·78 (ign.)	not estim.
	99·01	98·70	98·97

I. Porphyritic pink felspar of the Shap Fell granite: anal. J. B. Cohen.

II. Dominant felspar of the granite of Glenmalure, Co. Wicklow: anal. Galbraith; *cit.* Haughton, Quart. Journ. Geol. Soc. vol. xii. (1856) p. 173.

III. Groundmass of the Shap Fell granite: anal. J. B. Cohen.

The percentage of soda is worthy of notice; a small part of it is

* Rosenbusch, 'Mikr. Physiogr. d. petr. wichtig. Miner.' 2nd ed. (1885) p. 303. See also W. Maynard Hutchings, Geol. Mag. (1890) p. 264.

probably due to enclosed crystals of plagioclase; but, making liberal allowance for this, the potash- and soda-felspar molecules must be combined in the mineral in some such ratio as 4 : 1. The felspar resembles the dominant one in the granites of Leinster, investigated by Dr. S. Haughton, and the analysis of one of these is here quoted for comparison (II.).

Dr. Cohen has also analysed the groundmass of the granite: that is, the rock excluding the porphyritic felspars. From his figures (III.), and remembering that part of the potash must be contained in the mica, we see that among the smaller felspars of the rock plagioclase is the dominant variety. Comparing the figures in columns I. and III. with the bulk-analysis of the rock given above (p. 276), it is seen that the porphyritic crystals constitute about one-tenth of the whole mass of the rock (see column II. on p. 276).

The plagioclase felspar occurs in idiomorphic crystals, often enclosing zircon, dark mica, &c., but moulded by the quartz and later orthoclase; these facts sufficiently fix the time of formation of the mineral. Albite-twinning is always seen, the lamellæ being rather narrow. Carlsbad-twinning sometimes occurs in addition [395 *a*], and more rarely a lamellation answering to the pericline law [395, 876]. The optical properties point to oligoclase. The crystals are frequently turbid, being filled with a fine dust doubtless due to decomposition, and calcite is also to be detected, besides minute fan-like groups of fibres, probably of some soda-zeolite.

The quartz and later orthoclase call for no special remarks. The last-named mineral, being commonly the latest product of consolidation, is for the most part without crystal boundaries, and moulds the irregularly shaped or rounded grains of quartz (see Pl. XI. fig. 1). Micropegmatitic intergrowth of the two is not found in the normal type of granite.

The structure of the Shap Fell granite seems to warrant some inferences as to the conditions under which it was injected into its present position. The intrusion must have occurred soon after the close of the Silurian period. Taking the thickness of the Silurian strata as 14,000 feet, we obtain an approximation to the depth at which consolidation took place. By the consolidation of an igneous rock we must understand the consolidation of such of its constituents as crystallized *in situ*, and in particular of the one last formed, which in this case is the later generation of orthoclase. Earlier-formed minerals may have separated out from the magma at greater depths and been carried up to their present position. From a study of the fluid-cavities enclosed in the quartz of this rock, Mr. Clifton Ward deduced that it was formed under a pressure equivalent to the weight of 46,000 feet of strata, instead of the 14,000 which formed its actual cover; but this conclusion, as has been said, must be applied to the mineral, not the rock. It is improbable that the overlying strata would be able thus to withstand an upward pressure equal to more than three times their weight. Mr. Ward shows that, as regards this wide discrepancy, the Shap Fell rock is exceptional among the Lake District granites; but he fails to notice that it is

also exceptional in that its quartz crystallized prior to the final consolidation of the rock. If we suppose this mineral to have been brought up by the magma from its place of consolidation at a greater depth, the difficulty vanishes.

One of the most striking characters of the Shap Fell granite s the occurrence of distinct patches of darker colour and somewhat finer texture than the surrounding rock. These patches are abundant in the quarries, and may be well studied in the polished slabs and pillars used in building *. They are of rounded outline, though not usually spheroidal, and have a sharply defined boundary. Most of them are only a few inches to a foot or two feet in diameter, but there is one large enough to be separately quarried for setts. They contain, though rather more sparsely, porphyritic felspars like those of the normal granite; and Mr. Phillips gives instances of felspars lying partly in the dark patches and partly in the surrounding rock. The large felspars within the inclusions frequently have, however, a rather rounded outline, and present other peculiarities which will be described below.

It is evident that these phenomena cannot be explained by supposing the liquid granite to have caught up fragments of rocks broken through in its irruption and metamorphosed them to a crystalline condition. There are, indeed, some inclusions in the granite which represent highly altered fragments, but they are much less common than the type under consideration. They show a closer texture, and never enclose porphyritic felspars. Further, their form is quite irregular, and usually angular, and one large specimen in the Woodwardian Museum has evidently been a shaly or slaty rock, which has been partly split and penetrated by tongues of granite in the direction of its laminæ.

Leaving out of account evident included fragments, we have a type of inclusion possessing very definite characters, and agreeing with what is observed in many other granites, granophyres, and syenites. The inclusions are constantly of finer texture, greater density, darker colour, and more basic composition than their matrix. In the following table of silica-percentages the figures for the Shap Fell rock are obtained from Mr. Garwood, those for the other granites being quoted from Mr. J. A. Phillips's paper:—

	Matrix.	Inclusion.
Gready, Cornwall	69·64	65·01
Peterhead................	73·70	64·39
Ardshiel (Fort William)....	—	52·43
Shap Fell................	69·78	56·95

It will be seen that the difference between matrix and inclusion is greater in the Shap Fell granite than in those of Gready and Peterhead.

An average specimen of an inclusion from the Shap quarries was found to have a specific gravity of 2·769. This is considerably

* *E.g.* at the Midland Grand Hotel, St. Pancras Railway Terminus.

higher than the sp. gr. of the normal granite, and the difference is greater than in Mr. Phillips's rocks *.

	Matrix.	Inclusion.
Gready	2·72	2·73
Peterhead	2·69	2·73
Ardshiel (Fort William) ..	—	2·93
Shap Fell	2·687	2·769

It is interesting to compare the dark patches in the Shap Fell rock with those described by Dr. Ch. Barrois † in the intrusions near Rostrenen in Britanny. This, too, is a biotite-granite with large porphyritic crystals of orthoclase, which, however, are not red but white. In it occur patches of darker colour than the normal type, containing less orthoclase in the groundmass, more plagioclase, and that of a more basic variety, and more apatite. In these patches, however, the porphyritic crystals of orthoclase are wanting. This seems to be explained by the fact that these crystals, unlike those of the Shap rock, are of rather late consolidation, being posterior to the mica. In the Rostrenen rock, too, the patches are described as graduating into the normal rock, which would seem to indicate a greater degree of fluidity at the time of injection than in the case of the Shap granite.

Microscopic examination shows that these dark patches differ in some respects from the normal granite of the quarries, in both the relative proportions and the arrangement of the constituent minerals (see Pl. XI. fig. 2).

Apatite occurs rather plentifully, though locally, in small clear needles.

Zircon is less abundant, but a few crystals occur, chiefly in the mica.

Magnetite is present rather sparingly in little crystals and grains, as in the normal granite.

Sphene and dark mica occur in much greater abundance than in the typical Shap granite, and it is the latter mineral which gives the prevailing dark colour to the patches in question. It is mostly in rather small flakes, and shows much of the green decomposition-product noticed above. The sphene is sometimes almost as plentiful as the mica; it forms acute-angled crystals, as already described, or rounded grains, with deep brown colour and strong pleochroism.

The felspars here are almost constantly idiomorphic, and besides the porphyritic orthoclase, to be separately noticed, occur in larger and smaller crystals. Among these the triclinic felspar predominates over the monoclinic, and is more abundant than in the normal

* Among foreign rocks, the biotite-granite of the Barr-Andlau district in the Vosges compares very closely with that of Shap Fells. The figures given by Rosenbusch ('Steiger Schiefer,' pp. 147, 154, ed. 1877) are:—

	Matrix.	Inclusion.
Silica-percentage	68·967	57·894
Specific gravity	2·680	2·779

† Ann. Soc. Géol. du Nord, vol. xii. (1885) p. 6.

granite; it shows Carlsbad twinning, as well as fine lamellation on the albite-law. The orthoclase is in Carlsbad twins or simple crystals. Both felspars in the larger crystals exhibit zones of growth with slight variations of optical characters.

The quartz, which in the normal granite is of anterior consolidation to the orthoclase, has here been in general the latest mineral to form, and occurs interstitially in wedges, or often in granular patches. More rarely there is a micropegmatitic intergrowth of this mineral with part of the orthoclase [1046]. Again it is not uncommon to find isolated round grains of quartz, $\frac{1}{10}$ to $\frac{1}{4}$ inch in diameter, with no inclusions except an occasional grain of sphene; these must belong to a rather early stage of the consolidation [984, 1068–1070].

The porphyritic crystals of flesh-coloured orthoclase which occur within the dark patches are essentially identical with those in the normal granite, and must belong to a rather early stage of consolidation; but they present certain peculiarities which suggest that they have been subjected to chemical corrosion by the surrounding magma. They show very generally a somewhat rounded outline, and frequently have a well-marked narrow border distinguished by a white colour. Under the microscope it is seen that this border does not consist of orthoclase, but for the most part of plagioclase and quartz. The former is partly in lath-shaped forms, partly more irregular, and is moulded by the quartz. All the plagioclase crystals around any one orthoclase have a common orientation, presenting the usual crystallographic relation towards the monoclinic felspar, even when they have no point of contact with it. This fact, together with the rounded outlines of the central crystal and of the whole aggregate, point to the effects of corrosive alteration rather than an original intergrowth. It may also be observed that the border contains no inclusions other than those found in the orthoclase itself, as it would probably do if it were an actual addition of later date.

A singular modification of the granite is seen in a large loose block to the south-east of the intrusion and just below the footpath that runs along the north side of Wasdale Beck. Unfortunately we have not found this type *in situ*. Here, on a cursory examination, we seem to have something very like a gradual passage from the granite to a metamorphosed rock, or at least a contact of a very intimate character, the two rocks dovetailing into one another in a manner which makes it difficult to draw any definite line of demarcation between them. It seems as if little parallel veins of a pink felspathic rock proceeded from the granite penetrating the darker metamorphosed rock. In, or on the line of, these veins are large flesh-coloured felspars identical with those of the normal Shap granite; but the veins are sometimes too narrow to completely enclose these crystals, and the felspars also occur in the line of the veins beyond the point where these can be traced. The whole presents a striking resemblance to a section given by Dr. Ch. Barrois*

* Ann. Soc. Géol. du Nord, vol. xii. (1885) p. 15.

to show the dying-out of apophyses of the porphyritic granite of Rostrenen, which seems to have many analogies with the Shap Fell rock.

Any ideas based on the general appearance of this rock are, however, dispelled by a closer scrutiny, which proves that the whole is granite, and the semblance of a contact quite illusory. The granite differs somewhat from the normal type, especially in possessing a general "parallel structure." This parallelism is shown not only in the banding of the rock and the imitation of intrusive tongues, but also in the orientation of the large felspars and their restriction, for the most part, to particular lines. The pinkish colour of the rock along these lines must be referred to subsequent chemical action, as in the case of the pink granite in the quarries; and it here follows fine cracks which have probably served as channels for infiltration.

Slides of the rock [1071, 1280, 1281] show some curious characters. There is a distinct banded structure on a small scale. In some bands quartz is abundant, and then tends to be idiomorphic towards the felspar as in the normal granite; in other bands felspar is far in excess of quartz, and is then moulded by it, as in the dark patches in the quarries described above. Another link with these dark patches is the abundance of magnetite and apatite, but we have not identified any sphene. The rock, moreover, has peculiarities not found in either the normal granite or the dark patches. The magnetite, mainly occurring in streaks parallel to the banding, shows some crystal forms, but in some cases moulds the felspar. The brown mica is partly of early consolidation, but partly posterior to the felspars. Much of this mineral shows green coloration or bleaching, and finally conversion into a yellowish-brown substance with complete loss of the original structure.

The most striking feature, however, is the abundant occurrence of andalusite in idiomorphic, though rather rounded, prismatic crystals, usually coated with little flakes of yellowish or greenish-brown mica (see Pl. XI. fig. 3). The andalusite is usually clear and colourless, only occasionally showing the characteristic pleochroism:

α (c), pale rose-pink; β and γ, colourless or very faint green.

The inclusions are of magnetite, zircon, and mica, and around some of these, especially the zircon, the well-known pleochroic halo* is well seen, the colours being:

α (c), bright yellow; β and γ, colourless.

Andalusite as a regular constituent of granite has been recorded by Mr. Teall † and Dr. E. Cohen ‡ of Greifswald. As an accessory in granitic dykes it is also recorded in Spain §, Cornwall, and

* Rosenbusch, 'Mikr. Physiogr. d. petr. wichtig. Miner.' 2nd ed. (1885) p. 380.

† Min. Mag. vol. vii. (1887) p. 161.

‡ Neues Jahrb. (1887) vol. ii. p. 178.

§ Macpherson, Ann. Soc. Esp. Hist. Nat. vol. viii. (1879) p. 229.

Alsace*, while Von Gümbel† mentions it as occurring in pegmatite-veins in Bavaria.

In connexion with the parallel structure in this rock, it may be observed that at one place in the quarries the granite has a banded appearance not unlike some gneisses, a phenomenon doubtless due to a certain fluxional movement of the mass. In the general bulk of the granite the only indication of flow is an occasional rude parallelism of the long axes of the porphyritic felspars.

It remains to allude to some other special mineralogical and textural modifications exhibited in certain parts of the granite mass. It may be noticed that two varieties of the rock are recognized for building purposes, the difference being one of colour only. In both the large porphyritic felspars are of a flesh-red tint, but in the most common type the other felspars of the rock are white, while in the "dark" variety they too are red. The relations of the two rocks as seen in the quarry suggest that the latter is a modification of the former, produced by secondary actions, and connected with infiltration along fissures. This is certainly the case with some other granites, which are red in the neighbourhood of joint-surfaces, but grey in the interior. In one place in the Shap Fell quarry, extensive weathering along a main divisional plane, assisted perhaps by some degree of sliding, has converted the granite for some distance into a soft, greenish, earthy material.

The ordinary granite is in some places distinctly cut by small veins of a lighter coloured and somewhat finer-grained granite without porphyritic crystals. Although thus clearly posterior to the main intrusion, these may reasonably be referred to the same general source.

The texture of the normal granite itself seems to be very constant throughout the mass of the intrusion. It does not become finer in the marginal parts, nor, usually, in the nearest offshoots connected with it, so far as our observation goes; but the large porphyritic crystals are wanting in the small ramifying veins on the border of the mass, as if the narrowness of the fissures, though these are wide enough to contain the felspars, had offered some impediment to their floating in.

On the other hand there are, in one or two places at least, marginal modifications of the granite, which present a coarser texture than the normal type, as well as some mineralogical differences. This is seen on the hillside above Wasdale Head, about 350 yards N.W. of the farm. Here, at the contact with the metamorphosed rocks, the granite consists almost entirely of large crystals of pink felspar, with very little quartz, and the flakes of dark mica have the long blade-like habit already mentioned. Mica also occurs at the same place in the form of thin films adherent upon the crystal-faces of the felspar, which is partly idiomorphic. Again, the junction of the granite with metamorphosed ashes (altered to the appearance of mica-schist) is exposed in the tramway-cutting at the north-east

* Rosenbusch, 'Mikr. Physiogr. d. massig. Gest.' (1887) p. 31.
† Geogn. Beschr. Königr. Bayern, vol. ii. p. 317.

corner of the granite mass. Here a narrow band in the granite consists mainly of pink felspar, but has some quartz intergrown with it as a rude pegmatite [794–796]. There is also mica with the blade-like habit, as in the other case. The pegmatite band does not border the granite, but runs horizontally at right angles to the vertical face of junction.

A remarkable section is seen on the west side of Sherry Gill. Here the granite is seen underlying the altered rocks with a low angle of dip, and is probably a large sill rather than the main mass of the intrusion. Along the junction runs what at first sight appears to be a quartz-vein; but on examination it is found that the vein must have been a rather coarse-grained aggregate of felspar and quartz ("pegmatite" of some writers), in which the felspar has been largely replaced by quartz. The former mineral had often crystal outlines, and the process of replacement, which began in the interior of the crystal, is seen in various stages. A similar vein cuts through this, as well as through the granite and the metamorphosed rock, proving that veins of this kind were not all produced simultaneously.

As a somewhat analogous phenomenon may be mentioned a large cavity seen in the heart of the granite-quarries. It occurs in connexion with a joint, the surface of which is laid bare, and it has a width of about six inches from the joint-surface. This is lined with large felspars and quartz showing crystal faces, while around it is a narrow margin of pegmatite with graphic structure.

The geodes frequently contain well terminated crystals, and, in addition to the minerals mentioned, we have noticed in these and the joints talc, calcite, fluorite, malachite, iron pyrites, copper pyrites, molybdenite, and mispickel (?).

The replacement of the felspars by quartz at Sherry Gill, presumably an operation involving the agency of water, must belong to a late stage in the history of the intrusion. Perhaps we may assign to the same period the production of white mica along joint-faces in the metamorphosed rocks, accompanied by modifications extending to a very short distance from those planes. They have been observed in the Andesitic Group near Wasdale Pike, in the limestones of Wasdale Head Farm, and in the Coniston Flags of Wasdale Beck. Mr. E. H. Acton has kindly examined spectroscopically the mica from the last locality, and finds in it no trace of lithia; it is apparently an ordinary potash-mica.

§ III. The Dykes and Sills and their Relations to the Granite.

An interesting group of intrusions is well exhibited in a valley about a mile south of Shap Wells Hotel at Stakeley Folds and Gill Farm. Stakeley Folds is two thirds of a mile from the nearest granite outcrop. Here, and within three or four hundred yards to the south-east, four distinct sills are seen, injected one above the other at slightly different horizons in the Coniston Grits.

The highest sill, which, owing to the dip, is the lowest down the valley, shows a grey compact ground, studded with little quartz-grains and flakes of dark mica, and enclosing porphyritic felspars, some of which are one or two inches long. The quartz grains are mostly rounded, but occasionally a bipyramidal crystal is seen. The most conspicuous feature of the rock is the occurrence of felspars of flesh-red colour, some with Carlsbad twinning, which at once recall those of the Shap Fell granite, but have the rounded outlines and often the well-marked borders associated especially with the dark inclusions in that rock. Besides the above minerals, the thin slices cut from this sill [1157, 1158] contain apatite prisms, occasional zircons, and abundant acute-angled crystals of brown pleochroic sphene, like those so characteristic of our granitic inclusions. When the zircon is enclosed by mica, it is surrounded by an intensely absorbent pleochroic halo—a character which we have noted in the Shap Fell granite itself, and which is well known in many others. The mica is of the usual brown colour. Its mode of alteration is sometimes like that of the mica in the granite; while sometimes it gives rise to the interposition of lenticles and streaks of calcite along the cleavage-lamellæ in the fashion usually seen in lamprophyric rocks. The rounded grains of clear quartz have inlets and enclosures of the groundmass, which is that of an ordinary quartz-porphyry, in which, however, part of the felspar has separated out in little prisms. The porphyritic felspars enclose a few mica-flakes, as well as the earlier accessories. Both orthoclase and oligoclase are represented. The latter sometimes occurs in clusters of small crystals, with irregular junction with one another, but presenting crystal forms to the surrounding groundmass. Mr. Teall *, in describing similar clusters of felspar crystals in the Tynemouth dyke, has pointed out that this accords with the view that such crystals were formed under plutonic conditions, and floated up in the magma into their present position.

The next sill has, to the eye, a similar grey ground, with perhaps rather more mica, and encloses little plagioclase crystals and scattered grains of quartz about $\frac{1}{10}$ inch in diameter, but apparently none of the large red felspars. The microscopic characters accord with those of the former rock, except that there is very little sphene present [1159].

The preceding rocks may be called micaceous quartz-porphyries. The next sill has in the field a dull brown ground crowded with flakes of brown mica, and would naturally be mapped as a mica-trap. It contains, however, large red felspars with rounded outline, and a few scattered blebs of quartz. The microscope shows that these felspars are of a striated variety, probably near oligoclase, with a narrow border of orthoclase [1160]. The interior of each crystal is twinned according to the albite and Carlsbad laws, and the Carlsbad twinning is continued into the border of orthoclase. The slide contains abundant brown mica, which has suffered alteration chiefly of the kind producing calcite: there is but little mag-

* Geol. Mag. (1889) p. 481.

netite, either original or secondary. The groundmass of felspar and quartz is too far decomposed for minute examination, but it is clear that the rock has been of a much more acid type than such mica-traps as those found, for instance, in the Sedbergh district.

The lowest and thickest sill, at Stakeley Folds itself, consists of a quartz-porphyry in which the porphyritic elements are much more crowded than in the foregoing, forming a considerable proportion of the mass. The quartz grains are rounded, but with occasional idiomorphic faces, and the felspars comprise both orthoclase and oligoclase. The slice shows plenty of brown mica, altered into the green mineral along cleavage-planes [1161].

Two sills are seen near Gill Farm, farther down the same valley. The lower of these two is a red quartz-porphyry with little blebs of quartz. These average about $\frac{1}{10}$ inch in diameter, and have the usual "corroded" appearance, with enclosures of the groundmass, which is almost cryptocrystalline [1156]; there are, moreover, clusters of small porphyritic felspars like those noticed above. The upper sill has to the eye a much more lamprophyric appearance.

Not far east of Gill Farm is a large dyke which has all the appearance of an ordinary minette. No quartz is evident, but there are small porphyritic felspars, usually not more than $\frac{1}{2}$ inch long; some light red, others, with rounded edges, colourless and glassy. These latter are found under the microscope to consist of striated plagioclase with a narrow border of orthoclase, like those noted in the third of the sills at Stakeley Folds. As before, the two felspars have Carlsbad twinning in common [1155]. The brown mica has the usual hexagonal habit, but its extinction in transverse sections is oblique enough to show vaguely the repeated lamellar twinning already remarked in the granite. The flakes are frequently bleached in the interior, in the fashion familiar in the mica-traps of various districts. The inclusions of zircon, apatite, &c. are sometimes ranged parallel to the basal plane. Magnetite occurs in rather large patches through the rock, as well as in numerous minute octahedra. The general ground consists largely of little felspar prisms, with a few more shapeless crystals of concentrically zoned felspar, and subordinate quartz. Except for the quartz in the groundmass, which seems to be at least in part an original constituent, this dyke compares closely with mica-traps such as those described by Prof. Bonney and Mr. Houghton * in the Kendal and Sedbergh districts, and by Dr. Hatch † near the latter locality, or with similar rocks to be seen near Ingleton and in the district west of the Cross Fell range.

Viewed as a whole, the set of neighbouring intrusions briefly described above, while presenting a considerable range of differences, have at the same time some curious points in common. Further, while they have characters which seem to connect them on the one hand with the Shap Fell granite, and particularly with its darker patches, they are unmistakably linked on the other hand with the normal

* Quart. Journ. Geol. Soc. vol. xxxv. (1879) p. 165.

† Brit. Assoc. Rep. 1890 (Leeds Meeting), pp. 813, 814.

type of "mica-traps" found at greater distances from the Shap Fell intrusion. For instance, the rounded quartz-blebs, which are found in all the Stakeley Folds rocks, occur occasionally in mica-traps as far away as Swindale, near Knock, 14 miles from the granite, although there the groundmass contains no original quartz. The Swindale intrusions, too, have here and there a crystal of felspar, either of the red or of the colourless glassy-looking kind, the edges showing the rounding already noted in our rocks. The "glomero-porphyritic" clusters of small felspars have been noticed by Mr. Tate * in one of the Ingleton dykes. At the same time, the special characters of the Stakeley Folds rocks are met with more rarely at greater distances from the Shap Fell granite. From Prof. Bonney's descriptions we gather that of the seventeen dykes examined by him (at distances of 5 to 14 miles from the granite), only one had original quartz-grains, and he adds that "their appearance suggests the possibility of their having been caught up by the molten rock."

We do not find in published descriptions anything to compare at all closely with the above group of intrusions as a whole. It may be worth noting that the well-known "porphyroïde" of Mairus in the Ardennes, described by MM. de la Vallée Poussin and Renard †, is a biotite-quartz-porphyry in which the porphyritic felspars show phenomena of rounding and bordering in some respects similar to those noticed above.

The largest dyke in this part of the district is one exposed on the moorland some four or five hundred yards south of Wasdale Old Bridge. It strikes in a nearly N.W.–S.E. direction, and is remarkable for containing porphyritic crystals of monoclinic felspar (in the form of partially-interpenetrating Carlsbad twins nearly two inches long). It has also porphyritic quartz in good crystals up to $\frac{1}{5}$ inch, showing prism- as well as pyramid-faces; and these occur in great numbers enclosed in the large felspars, as well as in the general mass of the rock. The felspars have a very pronounced tabular habit, parallel to the clinopinacoid, the thickness of a crystal being less than one-fifth of its length. The forms present are the usual clinopinacoid, prism, basal, and hemidome, with another form $(h\,k\,l)$ not determinable on the specimens. The mineral has a strong glassy lustre, and the third cleavage (parallel to the orthopinacoid) is well developed. These characters, with the tabular habit, are the chief mineralogical grounds on which sanidine is usually separated from orthoclase, and there seems to be no reason why these crystals should not be named "sanidine."

A number of other dykes, showing in some degree a radial arrangement about the granite, are marked on the Geological Survey map, and we have examined several of these between Shap Fell and Tebay, and farther west and south. In many cases the rocks are deeply weathered, and detailed descriptions would not be very profitable. It is sufficient to note that some are ordinary quartz-porphyries; others are normal mica-traps with no original

* Brit. Assoc. Rep. 1890 (Leeds Meeting), p. 814.

† Mém. couronn. Acad. Roy. Brux. (1876).

quartz—*e.g.* the dyke between Crookdale and Borrowdale [1163]; while others, again, belong to intermediate types—*e. g.* the dyke or series of dykes on Potter Fell [792]. In this latter rock, at a distance of six miles from Shap Fell, are found long flakes of dark mica with the blade-like habit of that noticed in some parts of the granite margin.

None of the various intrusions we have alluded to can be traced as continuous with the granite at the present surface. If we are right in regarding them as apophyses, they are in connexion, not with the visible granite mass, but with a deep-seated extension of it.

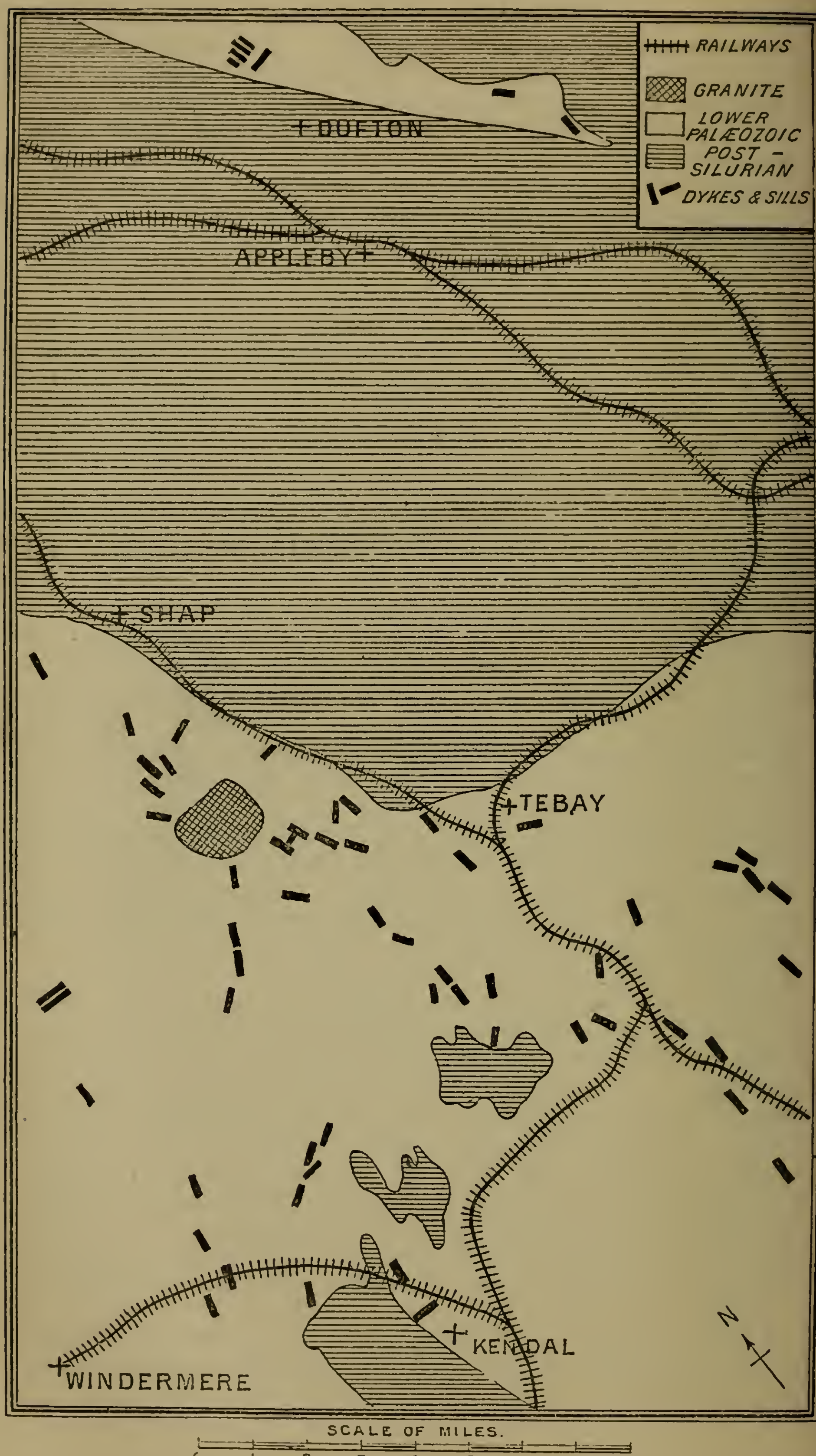
The small dykes found in close proximity to the margin of the granite outcrop, such as the two seen not far west of Wasdale Head Farm, are ordinary quartz-porphyries with no special peculiarities, except that they sometimes contain little crystals of brown sphene [757], an uncommon mineral in such rocks, though it might almost be expected in any offshoot of the Shap Fell granite. The same constituent occurs sparingly in the brown-coloured rock with porphyritic quartz and felspars which is prominent in the Blea Beck section, apparently forming an irregular sill at the summit of the Lower Limestone [882].

There is no doubt that many dykes which we have failed to observe exist to the north of Shap Fell. Such dykes would be less noticeable in the Volcanic Series than in the Silurians to the south, and the quarter-sheet of the Geological Survey map for the northern part of this district is not yet published *. Sedgwick found a quartz-porphyry not very different from that of Blea Beck in Wet Sleddale [803]. This may be a dyke or sill belonging to the inner group, connected at or near the surface with the Shap Fell granite. A large dyke belonging to the outer group of apophyses cuts the Skiddaw Slates at Goodcroft Farm, near Rossgill. It is about four miles north of the granite outcrop, towards which it bears directly. It is twenty to forty yards wide, and encloses entangled masses of indurated slate. The rock is a normal quartz-porphyry [1164].

When these apophyses are considered in conjunction with the patches of darker rock caught up in the mass of the granite, they appear to throw light upon the origin of several of the dykes which penetrate the Lower-Palæozoic rocks of the district, and which are thickly clustered in some areas, whilst they are much rarer in others. They abound within a radius of fifteen miles of the Shap granite (see Map, fig. 4, p. 290), whilst others are found in great numbers around the other granite areas. These latter are usually felsitic, whilst those more immediately in the neighbourhood of the Shap granite are both felsites and mica-traps, and, so far as we are aware, the latter are chiefly confined to the east end of the Lake District,

* [Since this paper was read we have, by kind permission of the Director-General, compared our map with the six-inch MS. map in the Survey Office, and inserted several additional dykes in the country north of the granite.—March 11th, 1891.]

Fig. 4.—*Sketch-Map showing the Distribution of Dykes and Sills around the Shap Granite.*



and to the Cross Fell, Sedbergh, and Ingleton areas, and do not occur around the Eskdale granite, though the minette of Sale Fell and the mica-traps of Dodd are near the granite of Skiddaw. Both the felsitic and micaceous rocks have abundant porphyritic felspars in the neighbourhood of the Shap granite, as we have shown in our description of the rocks from Stakeley Folds and elsewhere, and these felspars are in every respect so similar to those of the granite itself that it seems impossible to disconnect them from that mass, especially as we find that the felspars abound near the granite contact, and become rarer as we recede from this, whilst at the same time the more distant dykes show other indications of having consolidated at a greater distance from the then deep-seated magma, as evidenced by the occurrence of vesicles in the dyke at Castle How, near Tebay, which contains few porphyritic crystals. We have already pointed out the resemblances between these dykes and sills and the dark patches included in the granite. It would seem that a magma occurred beneath the Shap granite of a more basic character than the granite itself, and that from this the micaceous dykes were sent out, whilst the more acid portion of the magma was injected into rocks at a higher level than the main source of supply to form the Shap granite and the felsite apophyses, portions of the more basic part being carried up as "clots" in the granite, constituting the dark patches contained therein. In favour of this view, we may note that the evidence points to the Shap granite and the mica-traps having been formed at the same geological period, as shown by the intrusion of undoubted apophyses of the granite along with mica-traps in rocks of late Silurian age, whilst the pre-Carboniferous age of both the granite and the mica-traps is generally recognized. From the great abundance of mica-trap dykes it is evident that a magma like that which we suppose to have existed at a lower level than the Shap granite must have been situated at some point below this region, and the strong resemblance of the micaceous dykes of Stakeley Folds and the Gill to the patches in the granite almost certainly demonstrates that they have had a common source.

The possible presence of this more extensive magma underneath the Shap granite, and at one time connected with it, is of great importance in discussing the origin of the actual granite mass. In connexion with the foregoing observations, a few remarks concerning the nature of the intrusive mass of Shap seem to be necessary, though, in the absence of any certain knowledge, our comments must be brief.

We have attempted to show that the Shap granite is merely a subsidiary offshoot of a deep-seated igneous mass of much greater extent. It is interesting to observe that just as the Shap granite occurs at the point of contact of two sets of disturbances, viz. that which has produced the normal strike of the Lake District rocks, and that which gives the beds associated with the Skiddaw Slates to the west of the village of Shap a general N.W.–S.E. strike, so the principal dykes which we have attempted to connect with the

deeper-seated magma occur where the above-mentioned normal strike is complicated by the great fractures ranging down the Lune Valley in the neighbourhood of Tebay and Sedbergh.

We are now confronted with the question, what is the nature of the Shap intrusion itself? It does not appear to be a simple laccolite, and, on the other hand, we have seen that several sills are protruded from it around the margin. The strike of the rocks may have been bent by the granite, or, on the other hand, the intrusion may have taken place in a region where a weak place was caused, owing to the bending of the rocks. The usual greater density of the altered rocks seems to indicate some compression, though whether this and the preceding cause would be sufficient to leave space for the granitic intrusion is doubtful.

On the other hand, the abnormal alteration of the rocks around a mass with so small a diameter would suggest the passage of molten matter for a considerable period through the channel which is now filled with granite, though whether this channel ever communicated with the surface, giving rise to volcanic outbursts similar to those which occurred in regions farther north during Old Red Sandstone times, we have no evidence to show.

On the whole, the phenomena presented here seem to us to be most easily explicable upon the supposition that molten matter was for a long period forced from the underlying magma through a channel which may have been "punched out" in the way suggested by Dr. Ch. Barrois in the case of the Rostrenen granite *, and that it finally consolidated therein in the form of a "cedar-tree" laccolite, *i. e.* in a form corresponding with that of the gabbro shown in the theoretical representation drawn by Dr. A. Geikie †.

Lastly, in connexion with the deep-seated magma, one naturally recalls the magnetic observations of Profs. Thorpe and Rücker ‡ on the occurrence of a "ridge" in the neighbourhood of Appleby; but when we consider the subsequent injections of more basic rock in the neighbourhood, such as the Great Whin Sill, which was also doubtless connected with deeper masses of a somewhat similar nature, we are not inclined to lay much stress upon the coincidence.

§ IV. Metamorphism of the Surrounding Rocks.

A. *The Andesitic Group.*

The lowest rocks affected by the granite intrusion are those which may be classed as andesitic. Owing to the anticlinal folding described above, this group occupies a considerable area of ground to the north and west of the granite, being in contact with the intrusion around one-half of its circumference. The total thickness of the andesitic lavas is probably made up of a succession of comparatively thin flows; this is inferred from the fact that the rocks

* Ann. Soc. Géol. du Nord, vol. xii. (1885) p. 105.
† Trans. Roy. Soc. Edin. vol. xxxv. (1888) p. 142.
‡ 'Nature,' vol. xli. p. 598 (April 24th, 1890).

are vesicular throughout, and it is verified in one or two places where ash-bands are interbedded with the upper part of the lavas. The heterogeneous nature of the materials which constitute pyroclastic rocks makes it, however, difficult to classify them strictly into families. The ashes included here have probably a composition not very different from that of the andesitic lavas, and give rise by metamorphism to almost identical products, but they are not very sharply marked off from the overlying rocks which we place in the Rhyolitic Group.

Examined at a distance from the granite, as, for example, in Stockdale, the andesitic lavas are found to have suffered considerable changes by the ordinary processes of weathering. These changes—the destruction of the augite, the filling of the vesicles with secondary products, and the formation of little veins of calcite and quartz—date from a time anterior to the intrusion of the granite. This fact is abundantly proved by an examination of the metamorphosed rocks, and is essential to the interpretation of their phenomena. It must be remembered that this part of the Volcanic Series was perhaps subaërial, and rocks of this character were certainly exposed to denudation while the Coniston Limestone was being accumulated.

A section of the weathered andesite of Stockdale shows crowds of little felspar-prisms embedded in a pale green decomposition-product which appears to represent ophitic augite. The felspar may be referred by its extinction-angles to a variety near andesine in composition. A few larger felspar-crystals are scattered through the rock, and all are more or less turbid owing to secondary changes. The pale-green mineral polarizes in deep indigo tints, and shows the properties which seem to belong to delessite. There are none of the little bastite pseudomorphs so characteristic of decomposed rhombic pyroxenes in the hypersthene-andesites. There are apatite prisms and a few magnetite crystals of rude form, besides a certain amount of secondary magnetite-dust contained in the delessite. A little dust of calcite is also present, and a considerable amount of silica has been set free in the form of quartz.

The ovoid vesicles vary in size from one-twentieth of an inch to one or even two inches. The smallest ones are filled sometimes with quartz, sometimes with the pale-green product referred to delessite, which has a regular radiate arrangement. Others are lined with this substance, and have their interior occupied by confusedly crystallized quartz. The larger ones may have detached radiate aggregates of delessite in their centre, or more irregular patches due to the breaking away of the lining from the wall of the cavity before the silica was deposited. Other vesicles, again, are partly or wholly occupied by calcite, usually in a single crystal, and this kind of amygdule may often be seen side by side with the others here mentioned.

In a typical specimen of andesite taken between Wasdale Pike and Great Yarlside, where the metamorphism has been but slightly felt, Mr. Garwood finds 59·95 per cent. of silica. This confirms the

character of the rock, and compares closely with the figures found for other Lake District andesites. Two rocks from Mr. Clifton Ward's Falcon Crag section (near Keswick) gave 60·718 and 59·511 per cent., and one from Lingmell Beck, about two miles north-west of Scawfell Pike, 59·151 per cent. To these we may add a large boulder at Manfield, near Darlington, doubtless from the Lake District, in which Mr. W. F. K. Stock found 59·87 per cent. of silica *.

The andesitic lavas afford some of the most beautiful and instructive examples of thermo-metamorphism in the district, and as they can be followed along their line of strike from localities free from alteration into the "contact-aureole" and up to their junction with the granite itself, the process of transformation can be traced in all its stages.

At places at considerable distances from the junction, such as Little Saddle Crag (1350 yards), we notice that the vesicles contain a quantity of epidote in addition to delessite, quartz, and calcite [1277, 1278]. In some districts epidote has been recorded as a product of thermal metamorphism, but we cannot satisfy ourselves that in these andesites it is other than an ordinary result of weathering action. Setting it aside, the rocks at the locality in question give no marked indication of metamorphism by the granite. Proceeding eastward, however, we find substantial alteration setting in, being first shown in the weathering-products of the original rock. A specimen taken some distance west of Wasdale Pike, and nearly 800 yards from the granite-boundary, is crowded with minute flakes of brown mica, apparently developed at the expense of the decomposition-product (delessite ?) disseminated through the weathered andesite [1205]. In the vesicles part of the delessite is altered into green hornblende, while part remains unchanged (see Pl. XI. fig. 4). A little farther east (at 750 yards) the flakes of brown mica are rather larger and more collected [1204]. The pale green product in the vesicles is still only partially altered, and a little epidote is still present, but this mineral is not found nearer to the granite.

The formation of brown mica, which, it will be seen, is the most characteristic mineral in the altered andesites, is thus the first clear result of the metamorphic action, while, almost concurrently with it, green hornblende begins to appear among the contents of the vesicles. The greatest distance at which we have verified metamorphic action is 1150 or 1200 yards, on Low Fell, where the mica-flakes are chiefly collected about little grains of magnetite, a frequent occurrence in such rocks [1279].

In the field the early stages of metamorphism are indicated chiefly by the vesicles, in which lustrous, greenish-black aggregates of hornblende are to be detected by the eye. Proceeding towards the contact, the hornblende becomes more distinctive, showing good cleavage-planes, while the quartz filling other vesicles takes on a

* 'Naturalist' (1889), p. 304.

whiter and more evidently crystalline appearance, and stands out like pebbles on a weathered surface, often enclosing a kernel of hornblende. At the same time the dull grey ground of the rock becomes blacker and more compact, and often contains greenish crystalline streaks of hornblende, or more rarely a pyroxenic mineral in its place. Pyrites is of common occurrence in these streaks and in the interior of some of the vesicles. The dark colour of the rock is due to the development of mica, and nearer to the granite this mineral imparts a brown or purplish-brown sheen to the rock, and eventually becomes apparent to the eye. Near the contact the vesicles lose something of the distinctness of their external boundaries, their contents being to some extent merged in the general recrystallization of the rock.

The microscope brings out more clearly the nature of the transformations undergone by these rocks. The chloritoid substance which we identify with delessite is found to have disappeared completely in the thoroughly metamorphosed specimens. It is replaced most frequently by a deep brown, intensely dichroic mica, which is disseminated through the rock in very minute flakes, with occasionally a few larger ones in clusters and patches. This mineral occurs almost universally, but is not uniformly distributed. Instead of it in some parts of the sections we find a green hornblende, in crystalline grains of varying size, showing the prismatic cleavage-traces, and giving the usual absorption-formula:
γ, grass-green; β, a slightly less deep green; α, pale yellow-brown;

$$\gamma \overset{=}{_>} \beta >> \alpha.$$

With the hornblende, or locally replacing it, is seen occasionally a green fibrous actinolite in characteristic sheaf-like bundles. These amphibole-minerals are very generally confined to streaks varying from a very narrow width to half an inch or an inch, so that a slide may show hornblende as the characteristic mineral in one half of the field and brown mica in the other. Less common is a pyroxenic mineral, colourless in thin slices and having the general characters of monoclinic augite. It occurs in well-cleaved crystalline grains with the hornblende, and less frequently a vein is seen consisting entirely of a mosaic of crystalline augite [759].

Magnetite is a very common mineral, usually building minute but rather perfect octahedra. It is associated more frequently with the hornblende than with the brown mica, though the latter mineral sometimes encloses a few grains of magnetite also. Pyrites * is another mineral having the same association. It forms little cubical crystals or irregular patches. More remarkable is the very frequent occurrence of sphene, almost always in those parts of the altered rocks which contain hornblende. The sphene is in little rounded grains or clusters of minute granules, less commonly in rather imperfect crystal forms. It exhibits unusually strong

* Judging from the colours in reflected light, both pyrites and pyrrhotite occur, but it would be very difficult to isolate the little granules for examination.

pleochroism, between purplish-brown and colourless. Apatite occurs very rarely in little veins of quartz and mica, in a fashion which seems to indicate a metamorphic origin [798].

The above-mentioned minerals collectively make up a considerable part of the metamorphosed andesite. The remainder of the rock consists of a finely granular groundmass, the precise nature of which is less easily studied. A portion of it is quartz, but careful scrutiny detects here and there in the grains the evidence of twinning and even of twin-lamellation. It is doubtful in some cases how much of the original felspar of the andesites is preserved as such in the less metamorphosed examples. The process of reconstruction is seen, however, in some of the occasional porphyritic felspars. One of these will be found to be studded with little flakes of brown mica and partly transformed into a granular aggregate, while enough of the original felspar-substance remains to vaguely indicate the twinning between crossed nicols [799]. In the vicinity of the granite, the whole substance of the rock is certainly transformed, and the granular aggregate in which the coloured minerals are embedded assumes the perfectly clear appearance so well seen in many "crystalline schists." The twinning of the granules can be verified only occasionally, although it is evident from chemical considerations that a considerable proportion of the aggregate must consist of felspar. These highly altered rocks share with many of the products of dynamo-metamorphism their singular immunity from subsequent secondary changes, a property which seems to require some physical explanation. It is curious to compare in a junction-slice of altered andesite and granite the fresh minerals of the former with the turbid felspars and discoloured micas of the latter.

The contents of the vesicles and of certain narrow cracks posterior to the filling of the vesicles have undergone instructive transformations. It is here that the first effects of the metamorphic agent were manifested. The silica is found to have recrystallized in a mosaic of clear quartz-grains, free from fluid-cavities. In the less metamorphosed examples this process is incomplete, the central portion retaining its confused, almost cryptocrystalline, structure. In the highly altered rocks the change to a rather coarsely-granular mosaic is universal, and this at its outer boundary is not very sharply separated from the surrounding rock.

The delessite is here almost constantly replaced by the green hornblende described above, the brown mica occurring but rarely either in the vesicles or in the occasional narrow veins which represent cracks in the rock [798]. The vesicles contain hornblende even when the surrounding rock is densely charged with flakes of mica (see Pl. XI. fig. 5). The hornblende is well-cleaved, and sometimes the whole or a large part of the mineral within one vesicle is in crystalline continuity. One slide [897] shows one of the narrow veins alluded to running straight through the section. It contains clear quartz or, in some parts of its length, hornblende. The vein traverses two vesicles, and in each case the

portion of it within the vesicle is occupied by hornblende in crystalline continuity with the adjacent hornblende.

Little magnetite-crystals are not infrequently found in the altered vesicles, and sometimes pyrites. Sphene occurs in both the vesicles and the narrow veins, usually in round granules, occasionally in a characteristic acute-angled crystal. The metamorphic origin of all these minerals is abundantly proved by their manner of occurrence. In one instance only was a minute garnet found embedded in a quartz within the vesicle [759].

Felspar does not appear to have been commonly formed in the metamorphism of the contents of the vesicles. One slide only shows good crystals of that mineral, often twinned, occupying a considerable portion of some of the cavities, and accompanied by brown mica instead of the customary hornblende [1203]. This specimen was taken north of Wasdale Pike, about 400 yards from the nearest outcrop of granite. The felspar is here moulded by the mica, and occupies the marginal part of the vesicle (see Pl. XI. fig. 6).

The weathered andesites before metamorphism appear to have been traversed in places by little veins of chalcedony. One slide [1205] shows such a vein, now transformed into quartz, but retaining the mamillated form of deposit so characteristic of chalcedonic infiltrations. Other specimens, nearer to the granite, show veins of quartz-mosaic, which may or may not represent altered chalcedony, but are evidently recrystallized during the metamorphism of the rocks. Among other inclusions, this quartz contains minute patches of brown mica with rounded outlines [1201].

In the field the altered andesites sometimes show silvery mica on planes which seem to have been joints in the rock prior to the metamorphism,—a feature observed in some other rocks near the Shap Fell intrusion.

The distribution and association of the various minerals met with in the metamorphosed andesites seem to admit of a certain amount of explanation on chemical grounds, supposing that the substances formed at any point within the mass depended on the chemical composition at that point of the weathered andesite prior to the metamorphism. The phenomena described above, and especially those connected with the altered vesicles, sufficiently prove that considerable weathering had already taken place. It appears that the augite had been completely, and the felspars partially, destroyed, with the formation of quartz, calcite, and a chloritoid mineral as the chief secondary products. In accordance with their usual behaviour, the chloritoid substance was mainly in pseudomorphs occupying the place of the augite, but probably disseminated also through some of the larger felspars; the secondary quartz was confined mainly to the felspars; and the calcite formed granular patches or collected in veins and streaks. The vesicles were filled with quartz, or with calcite and the green product, or with the usual associations of these minerals, as already mentioned.

Taking the chloritoid mineral to be delessite and the brown mica biotite, the addition of some silica and the loss of most of the

water would be almost the only changes involved in the conversion of the former into the latter mineral, and this appears to have been the usual mode of alteration in the rocks in question. To produce hornblende, however, would require the taking up of lime, as well as silica, and the distribution of this mineral in patches and streaks in the metamorphosed rocks, and particularly within the vesicles, seems to show that its formation, instead of biotite, depended upon the presence of calcite in the immediate neighbourhood of the delessite. Augite contains much more lime than hornblende, and its mode of occurrence as a metamorphic mineral accords well with our suggestion. The veins of pure augite [759] may be taken as representing veins of crystalline calcite traversing the weathered andesite before its metamorphism. The mineral is identical with that to be described below as one of the most abundant silicates in metamorphosed rocks of the calcareous group, and is presumably a variety rich in lime.

With respect to the sphene, it is not easy to say in what form the titanic acid existed before the metamorphism. Ilmenite does not appear to be a common constituent of the original andesites, though it occurs rather abundantly, with secondary translucent sphene, in some of the ashy beds [766]. The sphene, a lime-bearing mineral, naturally occurs in association with the hornblende and colourless augite rather than with the mica, but the titanic acid may have been distributed uniformly through the weathered andesite and be now partly contained in the last-named mineral. The biotite of Miask is known to have 4·73 per cent. of titanic acid *, and this substance is beginning to be recognized as a widespread constituent of the brown rock-forming micas.

The magnetite, again, is mostly found in association with hornblende, but it is possible that the other parts of the rock contain as much iron, which is there incorporated as part of the brown mica. The flakes of the latter mineral are too minute to allow of any precise study which might determine whether they should be referred to biotite, haughtonite, or lepidomelane. The strongly pleochroic brown mica of thermo-metamorphic rocks (*Hornfels*, &c.) is usually stated to be biotite, but we shall allude to this point again below.

The specific gravity of a highly-metamorphosed vesicular andesite from near the northern border of the granite was found to be 2·800, the figures for the non-metamorphosed rock in Stockdale being 2·736. We shall see that the metamorphism of the rocks around the Shap granite is in general accompanied, as in this case, by a condensation of bulk.

In this place we may most conveniently notice the metamorphism of certain ashes, fine agglomerates, &c., which are closely associated with the andesitic lavas. The fragmental volcanic rocks, having usually a heterogeneous constitution, do not admit of any very strict

* R. Schläpfer, 'Rech. sur la compos. des micas et des chlorites,' Schaffhausen (1889). See also Koch, Zeitschr. deutsch. geol. Gesellsch. vol. xli. (1889) p. 165; W. M. Hutchings, Geol. Mag. (1890) pp. 272, 273.

classification into rhyolitic, andesitic, &c.; but the rocks in question seem to be made up largely of pyroclastic materials of the same general nature as the associated andesites, and give rise when metamorphosed to very similar results. They are probably on the whole somewhat more "acid" in composition, since they frequently enclose rhyolite-fragments broken up by the explosive outbursts by which the accumulations were produced, and mingled with the fine dust, fractured crystals, and andesitic material.

The non-metamorphosed rocks of this type may be studied in Stockdale, Wet Sleddale, &c., where the influence of the intrusion has not been perceptibly felt. The recognizable fragments are partly crystals, partly pieces of lava. The crystals are similar to those which occur porphyritically in the andesites themselves. They very frequently lie with their length nearly at right angles to the lamination of the finer matrix, indicating that they have been dropped into their place [895]. This appears to be a characteristic feature of pyroclastic rocks, especially those accumulated on land, and affords a useful criterion in other districts where ashes and lavas, chiefly of acid type, have been altered (not by thermo-metamorphism) almost beyond recognition.

Some of the lava-fragments are of andesite, showing the usual densely-packed felspar-prisms, and occasionally enclosing small vesicles [875]. Others are of rhyolite, as already remarked. The matrix of the mass is usually a finely-divided clastic material. Its lamination is emphasized by the development along it of a pale-yellowish or colourless sericitic substance which winds past the enclosed fragments, and imparts a "schist"-like appearance to the sections. Crystals, fragments, and matrix have undergone the ordinary weathering processes, with the production of secondary quartz, the usual pale-green product, a little magnetite dust, and some calcite, which is more uniformly distributed than in the weathered andesite lavas.

Metamorphosed representatives of these rocks, which we may term andesitic agglomerates and ashes, are met with intercalated among the lavas at various horizons. The minerals produced are in general those already described in the metamorphosed andesites. Mica is the commonest of the coloured constituents. It is usually of the highly pleochroic variety already noticed, giving a very deep, rather greenish-brown colour for vibrations parallel to the cleavage-traces. Sometimes it has less intense absorption, and is apparently partly bleached [875]; or again, it is partially decomposed, giving a green colour with secondary dust of magnetite. There is, however, a rather different type of mica seen in some of the slides, having a more ruddy brown colour and giving:

β and γ, chestnut-brown; α, nearly colourless.

This mica, when partially decomposed, loses its cleavage and some of its pleochroism. Its characters would seem to indicate a variety having a different chemical composition from the former, but although the two types usually occur separately, they are in some

cases associated in the same flake. Hornblende and actinolite both occur with the same characters as in the metamorphosed andesites [902 and 875], associated with one another, and in one instance with colourless augite [902]; but here these minerals are much less abundant than the mica, which is commonly the only ferro-magnesian mineral present in the slides. Hornblende, however, occurs as usual in the metamorphosed vesicles of enclosed andesite-fragments [875].

Magnetite is found in octahedra and less perfect forms [796], but it is less abundant than in the metamorphosed andesites, and is often wanting in those specimens most rich in mica [896, etc.]. Sphene has not been observed. These facts accord with the suggestions offered above; the titanic acid and most of the iron oxides contained in the rocks have been incorporated in the brown micas.

The remainder of the rock is a granular aggregate resembling that seen in the metamorphosed andesitic lavas, though not quite so fine-grained. Twinning and twin-lamellation are to be observed between crossed nicols, and it is evident that a large part of the rock consists of reconstituted felspar. This is brought out also by a certain amount of turbidity in the felspars, distinguishing them from the clear quartz, which they sometimes mould. It is noticeable in these metamorphosed andesitic rocks that the originally fragmental examples show signs of subsequent weathering which are not found in the associated lavas.

The embedded felspar-crystals have been replaced by an aggregate of new felspar and quartz, with more or less brown mica, and exceptionally a considerable quantity of yellow epidote [900]. In the less metamorphosed examples the original twinning can be vaguely discerned; in specimens taken close to the granite-junction the structure is totally destroyed, and the pseudomorphs are recognized merely as areas poorer in mica than the surrounding rock.

The character of the metamorphosed andesitic ashes and agglomerates is sufficiently indicated by the foregoing remarks. It only remains to be said that there is often a marked laminated structure well indicated by the parallel disposition of the flakes of mica [797, 896], and increasing the general resemblance of these highly altered rocks to true crystalline schists.

In the thermo-metamorphism of rocks in the vicinity of an igneous mass, it is an important question how far the total chemical composition has been modified by the changes produced. To give a satisfactory solution of this question would demand a detailed chemical investigation. With respect to the andesitic rocks of Shap Fell, Mr. Garwood has examined for us specimens of highly altered andesite and ash from near the northern margin of the granite, and finds that they contain only 50·75 and 50·90 per cent. of silica respectively; *i. e.* 9 per cent. less than the non-metamorphosed andesite. This apparent loss of silica is a fact for which we are unable to offer any explanation. There is no stratigraphical reason to suppose that the specimens analysed differed in their original composition from normal augite-andesites such as those

of Stockdale, but they probably do not occupy quite the same horizon.

Thermo-metamorphism in andesitic rocks has hitherto received but little attention. Prof. Judd * has adverted very briefly to some changes of this kind in the andesites or "propylites" of the Western Isles of Scotland. He alludes to the formation in the contact-zones of colourless secondary pyroxene, magnetite, and deep brown biotite, with possibly melilite and felspar; but we do not gather that these phenomena are exhibited on any extensive scale. As regards the metamorphism by heat of augitic rocks in general, the first important record is that of Mr. Allport †, who showed that in the neighbourhood of the Cornish granites the augite of the "greenstones" has been replaced by hornblende and actinolite. It appears from his description, and from the only Cornish examples we have examined, that there, as in the Shap Fell andesites, much at least of the augite must have been converted into secondary minerals before the metamorphism [1129]. Prof. Lossen ‡, however, describes appearances in the metamorphosed diabases in the Harz, which leave no doubt as to the direct "uralitization" of augite under the influence of a granitic intrusion; and a series of slides from specimens taken near Rosstrappe, Thale, one of his typical localities, show that hornblende has been formed both directly from augite and also from its decomposition-products [469–473]. The officers of the Geological Survey of Saxony § have described the conversion of diabases into actinolite- and anthophyllite-schists around the syenite of Meissen.

B. *The Rhyolitic Rocks.*

The rhyolites of the district, whether associated with or underlying the Coniston Limestone, have characters familiar to geologists who are acquainted with Ordovician volcanic rocks in other parts of Britain, and we do not propose to enter into many details with respect to their general features. Moreover, owing to their comparatively simple chemical and mineralogical constitution, they do not present such diversities in their modes of metamorphism as have been described in the case of the andesites. In the field, indeed, the rhyolites seem to show little or no change, as they are traced along their strike into the aureole of metamorphism; but this idea is dispelled by a closer study of the specimens.

At a distance from the granite, the rhyolites may be studied in Stockdale and Long Sleddale. They often have a grey colour with a rather flinty appearance; when this is wanting, they are pink or cream-coloured, but always of compact texture. One type is laminated parallel to its flow-lines, and often has a fissile structure in

* Quart. Journ. Geol. Soc. vol. xlvi. (1890) p. 370.

† *Ibid.* vol. xxxii. (1876) p. 418.

‡ 'Erläut. zur geol. Specialk. Preuss.,' Blatt Harzgerode (1882), pp. 79, &c.

§ 'Erläut. zur Specialk. d. Königr. Sachsen' (1889), K. Dalmar, Section Tanneberg, Blatt 64; A. Sauer, Section Meissen, Blatt 48.

the same direction. Another is coarsely nodular, the spheroidal nodules varying from an inch to a foot in diameter. Such nodular rhyolites are well known in other districts, and have been discussed by one of us in the case of the Ordovician lavas of Caernarvonshire *. The alterations there described in what appear to have been giant spherulites, and in particular their partial and total replacement by cryptocrystalline silica or quartz, are exhibited on a magnificent scale on Great Yarlside and at other localities in our district. The peculiarity is not confined to true lava-flows; for an apparently intrusive rock in Blea Beck plantation, near Shap Wells, contains good silicified spheroids.

The rhyolites are never notably porphyritic, resembling in this and other respects the corresponding rocks in North Wales. Indeed the microscope shows that much of the material of the rocks was but very imperfectly individualized into felspar and quartz, presenting rather the features which are referred by many English petrologists to devitrification. Vesicles are found in these rocks only rarely, and they are usually of microscopic size.

An idea of the chemical composition of the rhyolites may be gathered from Mr. Garwood's analyses given below; the figures for two Caernarvonshire rocks are quoted for comparison. It will also be seen from columns I. and II. that, whatever metamorphism has operated in the rhyolite near the granite-contact, it has not materially affected the bulk-analysis of the rock.

The specific gravity of the specimen (I.) analysed is 2·608, which agrees exactly with that of similar rocks from North Wales. One of the most metamorphosed rhyolites from Wasdale Head gave 2·623, showing no great difference.

	I.	II.	III.	IV.
SiO_2	75·95	76·95	74·88	77·5
Al_2O_3	13·77	15·50	12·00	9·7
Fe_2O_3	3·48	2·00	3·50	6·1
FeO	not estim.	not estim.	0·20	not estim.
MgO	trace.	...	1·28	...
CaO	0·25	1·05	0·34	...
Na_2O } by difference			2·49	0·3
K_2O } by difference	6·55	4·50	4·77	5·8
(Ignition) } by difference			1·20	0·4
	100·00	100·00	100·66	99·8

I. Spherulitic Rhyolite, Stockdale; anal. E. J. Garwood.
II. Nodular Rhyolite, close to granite, near Wasdale Head Farm; anal. E. J. Garwood.
III. Rhyolite, Pitt's Head, 2½ miles S.W. of Snowdon; anal. J. Hughes, Trans. Roy. Ir. Acad. vol. xxiii. (1859) p. 615.
IV. Rhyolite, Cwm-silyn, above Nantlle Valley; anal. E. Hamilton Acton and J. T. Hewitt; 'Bala Volc. Ser. of Caern.' (1889) p. 13.

A very characteristic rock is that which forms the lower part of the Coniston Limestone rhyolite at Stockdale and Long Sleddale. It is of the laminated, fissile variety, the overlying rock being

* 'The Bala Volcanic Series of Caernarvonshire' (1889), chap. iii.

nodular,—an arrangement noted in some other localities also. This laminated rock has a typical microspherulitic structure, being almost entirely built of densely-packed minute spherulites, each of which gives a distinct black cross when a section is examined between crossed nicols [861]. In some places the growth, instead of being centric, is linear, and then follows the lines of flow. Slighter differences in structure in different parts of the slide also follow the fluxion-lines. A beautiful figure of this rock, showing the microspherulitic and perlitic structures, has been given by Mr. Teall *, and the same rock has been described and figured by Mr. Rutley †. The latter author has expressed the opinion that the spherulitic structure is here an effect of devitrification subsequent to the perlitic cracking; but we are unable to see that he has given any reasons for this view. The practice of assigning a secondary origin to special structures in the older acid lavas has perhaps been pushed to excess in some quarters. In the Westmorland rhyolites there are traces of perlitic fissures traversing rocks which are now microcrystalline, and other appearances pointing to the alteration of an originally glassy mass; but we find nothing to suggest that the spherulitic and allied structures are of formation posterior to the consolidation of the lava; and the breaking up of the vitreous material of the rocks examined seems to have been in many cases a chemical, not merely a molecular change.

In addition to occasional small crystals of quartz and felspar—mostly plagioclase—the only original minerals found in these rhyolitic lavas are scattered magnetite-crystals, and very rarely prisms of apatite [802]. Probably a little augite or biotite formed part of the original rocks, but a few scraps of the usual pale-green decomposition-product are the only thing to indicate the former presence of these minerals. Another secondary constituent is a yellowish-brown filmy mineral, like sericitic mica, which usually occupies perlitic cracks.

A frequent type of alteration in the rhyolites, shown in many of our specimens, is what we may conveniently term "silicification." The groundmass of rocks so affected presents a finely crystalline appearance, and consists mainly of quartz in a fine-grained mosaic, passing in irregularly disposed patches into a rather coarser grain. Included crystals of felspar are frequently pseudomorphed by a similar quartz-mosaic, and the process is sometimes made very evident by portions of the twinned crystals remaining still unaltered [802]. The occurrence of these silicified rhyolites shows no relation to the proximity of the granite, and we do not ascribe it to metamorphism by the agency of the intrusion. Identical phenomena are observed in various localities in Caernarvonshire remote from any igneous intrusion, and Miss Raisin ‡ has suggested a "percola-

* 'British Petrography' (1888), pl. xxxviii.

† Quart. Journ. Geol. Soc. vol. xl. (1884) p. 345, pl. xviii. fig. 6; Mem. Geol. Surv. (1885), 'The Felsitic Lavas of England and Wales,' p. 12, pl. ii. fig. 1.

‡ Quart. Journ. Geol. Soc. vol. xlv. (1889) p. 267.

tion of heated waters carrying silica in solution" during a "Solfatara-stage" which may have marked the decline of Ordovician vulcanicity in the area. Whether this explanation hold good or not, it is difficult to believe that the alteration observed in some of these rocks could be effected except by the introduction of silica in some manner; and this addition of silica from without probably explains the high percentages of that substance found in some published analyses of rhyolites.

Passing on to the thermo-metamorphism of the rhyolites, we find a few points worth recording. Specimens taken north and east of the spot marked "Tunnel," at distances of about 600 or 700 yards from the margin of the granite, have suffered some alteration of the groundmass, which is in places of a microcrystalline texture, showing felspar as well as quartz. This is apparently quite reconstituted, but curving perlitic cracks are still clearly evident throughout the mass, marked out by micaceous films. The rock here encloses small porphyritic felspars, which are either quite unaltered or partly silicified, as mentioned above. One specimen has numerous vesicles, which are filled by crystallized quartz, partly idiomorphic; and there is no evidence that this quartz has recrystallized under metamorphic action [801].

Near Wasdale Head Farm the rhyolite may be examined close to its junction with the granite, and here more distinct evidences of metamorphism are obtained. Some specimens show a microcrystalline aggregate of recognizable clear felspar and quartz, similar to that noticed in the metamorphosed andesites, and leaving no doubt that the whole has been reconstituted by metamorphic agency [907]. Other examples seem to have been silicified prior to the intrusion of the granite, and the quartz which forms most of their bulk cannot be stated with certainty to have recrystallized during the metamorphism [880, 881]. The same is true of the quartz-veins which traverse some of the slides, the quartz in them often showing partial crystal contours. Besides quartz and felspar, these metamorphosed rhyolites have minute flakes of pleochroic brown mica and some colourless mica giving brilliant interference-colours. Larger flakes of brown mica occur, grouped in a fashion which suggests their derivation from the pale-green decomposition-product seen in some of the non-metamorphosed rhyolites. A pyrites-mineral, in good crystals, is an occasional constituent of these altered rocks [881].

The nodular rhyolites show considerable modifications in specimens taken near the granite. They must have undergone, before metamorphism, the process so common in these rocks, by which some of the constituents of the nodules became segregated into concentric shells, and these have been variously affected by the metamorphism. We find some bands in the sections consisting almost entirely of moderately coarse quartz-mosaic, with a little mica, either dark or pale, and occasionally crystals of blue tourmaline [907]. These correspond to the flinty shells seen in the nodules of many rhyolites, the silica, which was probably cryptocrystalline, having been trans-

formed into thoroughly crystalline quartz. Such bands alternate in the slides with others composed of a minutely crystalline aggregate of felspar and quartz, probably representing shells of rhyolite, which had not been much altered before the metamorphism. Again, parallel with these alternating zones there are sometimes strings of mica-flakes, mostly brown, but some colourless, which seem to answer to the well-known shells of the substance which Mr. Grenville Cole has compared with "pinite."

We now come to the rocks which we have classed as rhyolitic ashes and breccias. Owing to the much faulted state of these rocks and the want of continuous sections in some critical places, the precise succession in the Rhyolitic Group is a matter of inference rather than of demonstration. The order of the rocks actually exposed seems to be as follows, in descending order :—

Rhyolite, faulted against the Lower Coniston Limestone in Blea Beck.

Breccias and ashes, seen in the Summit railway-cutting and to the south, and on the moor west of the Hotel; these in Blea Beck rest on

Rhyolites, east of Blea Beck Bridge.

Fine ashes seen beside the old road to the north of Blea Beck Bridge; these have an abnormal strike (east and west) and their horizon is therefore rather doubtful.

Rhyolites, with subordinate fine ashes, covering the tract north of Blea Beck between the old and new high roads.

Fine ashes, with subordinate breccias, seen on the eastern margin of the granite and on the high road and neighbouring moorland; also on the west side of the granite, occupying the ground from Wasdale Pike to near Wasdale Head Farm.

On the whole the fragmental rocks of the upper part of the group, which are entirely missing on the west side of the intrusion, contain a larger proportion of macroscopic fragments, mostly of pink rhyolite, than those of the lower part, so that, in the field, we have termed many of them breccias; but the presence of these relatively large fragments in the fine matrix is the only character to distinguish the breccias from the associated rocks mapped as ashes. The rhyolite fragments are often angular or subangular, as in many similar rocks throughout the Lake District, and are clearly the results of explosive volcanic action. A comparison of the numerous rocks of this type in the Borrowdale series seems to show that the fragments cannot in general be ascribed to rhyolitic lava-flows broken through by the eruptions, but must represent a shattered crust of rhyolite formed within the volcanic vents.

The fragments in our breccias are by no means so exclusively composed of acid lava as might be supposed from the prominence of the pink rhyolite upon the dark matrix. Andesite is also well represented, in fragments of generally subangular or rounded form, besides occasional pieces of quartz-porphyry [1076, &c.], abundant

crystals of felspar, often silicified, quartz, magnetite, &c. The rolled appearance of some quartz grains and other fragments seems to indicate a detrital source for part of the material, and there can be no doubt that most, if not all, of these rocks were formed under water.

In the ashes of the lower part of the group, the fine matrix encloses only a few minute grains of quartz and occasional felspar-crystals, but in some of the upper fragmental rocks of the group we find a coarser-grained mass wherein identifiable fragments of minerals and rocks are in excess of the matrix which unites them [1073]. Despite such variations as this, it will be best to consider the whole of the ashes and breccias together, with respect to the effect on them of the metamorphic action produced by the granite intrusion. Even the rocks seen on the moorland west of the Hotel, some of which would be described as ashy grits rather than ashes [1074, 1075], show in their matrix the same metamorphic changes as the ordinary fine-grained ashes.

The fine ashes and the matrix of the breccias, when not extensively altered, present the same general characters as the ashy beds associated with rhyolitic lavas in other districts, such as North Wales. There is usually a distinct lamination, rather wavy so as to resemble a flow-structure, and this is often marked out by films of a colourless or yellowish sericitic substance [766, 767]. The general mass, consisting of very finely divided material probably analogous to volcanic dust, offers no special peculiarities. The decomposition-products are of the ordinary kind and often include a considerable quantity of epidote. The embedded felspar-crystals especially are in some of the rocks completely pseudomorphed by aggregates of greenish-yellow to colourless epidote, but we see no reason to connect this mineral with metamorphic action in the ordinary sense. More important is the formation of secondary quartz in the manner already noticed in the silicified rhyolitic lavas. This has taken place prior to the intrusion of the granite, and even in the inner part of the contact-aureole has to a great extent protected the rocks so affected from further changes.

The metamorphism of the rhyolitic ashes is in some respects comparable with that of argillaceous strata, such as the Brathay Flags, and it makes itself felt to about the same distances. The breccia of the Shap Summit railway-cutting shows no decided alteration of a thermo-metamorphic nature, the induration of the compact black matrix being attributable to a certain formation of secondary quartz, which probably took place before the date of the intrusion. This is at 1400 or 1500 yards from the granite. Farther south, a similar rock, though with fewer visible fragments, is exposed by the side of the footpath, about 1250 yards from the granite-margin, and this is within the metamorphosing influence. Under the microscope it shows at least a superficial resemblance to the spotted Brathay Flags described below in the occurrence of minute spots, about $\frac{1}{50}$ inch in diameter, free from the brown pigment which crowds most of the field [859]. The spots sometimes show between

crossed nicols a distinct crystalline reaction, polarizing in low tints like those of quartz. The brown colouring-matter is too minutely divided and too densely collected to admit of determination, but it is probably to be referred to mica. A similar substance is found in the metamorphosed fine pyritous ashes north of Blea Beck Bridge, and here it is certainly brown mica, the flakes being large enough for the pleochroism and other characters to become evident [869]. Here too, at 650 to 700 yards from the granite, the light spots are larger (up to about $\frac{1}{10}$ inch in diameter), but only the smallest of them behave in polarized light as single crystals. It may be remarked in passing that the andesite fragments in the breccias show the same development of brown mica as the matrix [1072, 1166].

There can be no doubt that the brown mica in these rocks is of metamorphic origin. It is absent in all specimens taken at places remote from the granite, and, up to a certain point, becomes more distinctly separated out, and in larger flakes, as we approach the intrusion. In some cases the mica is seen to have been formed especially in the neighbourhood of crystals of magnetite, from which the mineral presumably obtained the iron necessary for its composition. This is seen in some of the rocks which crop out on the moor west of the Hotel, about 1000 yards from the granite-boundary [1076]. Some of the rocks in this neighbourhood, however, show but little modification which can be ascribed to thermal action [1073], making it appear that the metamorphism does not depend in a very strict manner upon distance from the intrusion; but, in view of the faulted character of the ground, it would be unsafe to draw any conclusions from this fact.

We pass on to consider the more complete metamorphism of rhyolitic ashes seen in exposures nearer to the contact. About 250 yards from the eastern margin of the granite some highly altered ashes are exposed in a disused quarry on the old Shap road, and similar rocks crop out at one or two places on the neighbouring moorland. Almost every trace of original constitution is lost, but what remains is sufficient to show that the rocks were felspathic ashes. The lamination is indicated by the arrangement of flakes of brown mica and by streaks rich in opaque iron ores. The mica seems to have been derived from a green chloritoid mineral with low polarization-tints, some of which remains unaltered. The iron ores include ilmenite as well as magnetite, and occur as little crystals and minute granules having the appearance of metamorphic products. A clear colourless mica is sparingly present, and a characteristic mineral is disthene, of the pale blue variety known as cyanite, which is abundant in the slides in little imperfect crystals and clusters of granules. The bulk of the rock, however, consists of a fine-grained crystalline aggregate of felspar. The water-clear crystals mostly show some approach to rectangular contours, the cleavage is often well seen, and twinning is not uncommon; but we are not able to say with certainty that quartz is not present in subordinate quantity. It is evident, at least, that the bulk is of felspar, and that the whole was formed *in situ* during the metamorphism.

The optical characters of the grains seem to indicate orthoclase and albite. In a few places this groundmass encloses fine needles of a mineral with very high refraction and double refraction, straight extinction, and occasionally a faint brown colour; this seems to be rutile [905]. It will be noticed that in the andesitic rocks, with their higher content of lime, sphene was formed instead of rutile.

These ashes have had a few felspar crystals, up to about $\frac{1}{10}$ inch in length, scattered through the rock. The crystals are now for the most part replaced by new felspar substance, which does not preserve the original orientation; but enough of the old cloudy felspar remains to prove its nature and to show its twin-structure [904].

Rocks of similar appearance to the above are seen on the west side of the high road, where they strike parallel to the neighbouring granite-boundary, with a dip to the east. A specimen was examined from the little "sike" marked on the map [903]. Here the metamorphism seems more complete. Cyanite, colourless mica, and the green chloritoid substance are absent or rare, and the conversion of the last-named into dark mica is seen in various stages. Some of the mica is green, but most of it is brown with intense pleochroism. There are a few comparatively large flakes, and these enclose little prisms of apatite. The recrystallization of the groundmass is complete, but there is the same difficulty in determining to what extent quartz may enter into it as well as felspar. There is undoubted quartz in little veins following the general lamination of the rock as indicated by the mica-flakes. Iron ores are again rather abundant, and are of more than one kind.

The red highly-metamorphosed rock in contact with the granite in the little ravine behind Wasdale Head Farm is identical with those just described from the eastern margin of the intrusion. Magnetite and brown mica are tolerably abundant; cyanite is sparingly distributed; apatite occurs both in the larger mica-flakes and in the general groundmass, which consists as before of an aggregate of clear felspar in minute crystals [764].

The southern slope of Wasdale Pike is occupied by a succession of highly altered ashes, which, as already stated, we class with the Rhyolitic Group. They are faulted on the north side against the andesitic rocks, on the south against the Coniston Limestone group. They show plenty of dark mica, have a very distinct lamination, and give in the field a suggestion of crystalline schists or even gneisses. At some horizons the presence of fragments of the usual pink rhyolite gives the rocks the character of breccias. There is often some admixture of detrital material, chiefly indicated in the slides by angular clastic grains of quartz [1167]. The general features show only minor variations from the types just described. Recrystallized felspars, probably accompanied by quartz, make up the bulk of the rock; magnetite and brown mica are universally present; colourless mica, cyanite, and apatite occur more sparingly and occasionally. The original felspar crystals are always completely replaced by a mosaic of new felspar, and the little areas are often bordered by magnetite with some brown mica

[1168]. In one of the lowest rocks exposed the mica is clustered in little ovoid patches about $\frac{1}{10}$ inch in diameter [1132]. This is close to the granite.

These rocks differ from the other metamorphosed ashes, which we have classed as andesitic, not only in the presence of certain aluminous and other minerals, but in the smaller proportion of brown mica and the absence of the lime-bearing silicates, augite and hornblende. Only one of our specimens, from the uppermost bed exposed, shows green hornblende as well as brown mica. The two minerals are not mingled, but occur in alternate narrow bands, about twenty in an inch [763]. Possibly this rock originally contained some calcareous matter, as well as clastic grains.

The thin ash-beds associated with the rhyolite in the Coniston Limestone group have not been minutely examined, and it would probably be difficult to separate them, within the zone of greatest metamorphism, from the impure limestones. Near Wasdale Head Farm, however, a laminated white rock occurs between the Upper Limestone and the underlying rhyolite, which perhaps represents the flaky ash seen in a similar position in Blea Beck. In a section [1044] it is seen to be composed in great part of minute scales of colourless mica. These are collected in densely matted masses with a rough parallel orientation, and also occur in rather larger flakes associated with the usual brown pleochroic mica. In the same slide are seen very imperfectly separated crystals giving brilliant interference-tints and possibly referable to pyroxene (?).

Finally, it should be noticed that in ashes which had already suffered silicification the metamorphism seems to have been limited to the production of brown mica, which forms streaks and clusters of small flakes mostly surrounding grains of magnetite. Rocks of this type show no difference between specimens taken close to Wasdale Head Farm, among intensely metamorphosed beds [879], and others from a quarry on the high road nearly 800 yards from the granite-margin.

C. *The Coniston Limestones.*

As exposed in Blea Beck plantation, in the grounds of the Hotel, the calcareous rocks show few signs of metamorphism. The purest beds, such as the highest seen at this locality, have a finely crystalline texture, and consist simply of a fine mosaic of calcite grains, with little or no foreign matter [871]. With other beds the case is different, and some are rather of the nature of calcareous shales with nodular bands of less impure rock. The matrix of the Calcareous Breccia is sometimes a tolerably pure limestone, which, like the preceding, has recrystallized to a calcite-mosaic, crowding the dusty impurities into particular patches [862]; but at other times there is much more non-calcareous material, which seems to be mostly of volcanic origin. The base of the breccia, indeed, may be described rather as a calcareous ash [870]. The fragments in the breccia are for the most part angular pieces of pink rhyolite, similar

to those in the volcanic breccias and perhaps of direct volcanic origin; but there are also fragments of decomposing andesite with vesicles filled with calcite, and rolled crystals of striated felspar [862]. Some of the lower beds exposed in the Upper Coniston Limestone division are more gritty in appearance, and one contains plenty of rounded quartz and fragments of spherulitic rhyolite, as well as ashy material [1077]. This bed is interposed between two flaky agglomeratic ashes, and the admixture of volcanic material with the detrital and calcareous is very clear. The Lower Coniston Limestone here offers no characters which call for notice.

Although the limestones in our district cannot be followed in continuous exposures from the unaltered to the highly altered state, we can obtain a general idea of the extent and progress of the metamorphism by comparing specimens from different spots. As already stated, the Blea Beck rocks are in general unaffected by any thermal metamorphism, but one or two specimens show the beginning of the change in the development of a few scraps of a pyroxenic mineral, evidently formed at the expense of part of the calcareous material. This is at 1400 yards from the granite [870]; (compare with [1077] from the same locality, which is quite unaltered). A specimen taken west of the small plantation near Wasdale Beck, about 1000 yards from the granite, shows more of the lime-silicate with less calcite [906]. This rock, like the preceding, is a calcareous ash, though it belongs to a lower horizon. We shall notice in its proper place a calcareous rock in the Silurians, which is well seen at Packhouse Hill, about 600 yards from the granite. There lime-silicates are abundantly present, and only a rare patch of the original calcite is to be seen [1225]. Finally, in the exposures of Coniston Limestone near Wasdale Head Farm, at distances of 300 yards and less from the contact, all trace of the original calcareous ingredient is merged in metamorphic products. The progressive modification thus indicated is more gradual than that recorded in Lossen's metamorphosed limestones around the granite of the Ramberg.

In the Wasdale Head section, as already stated, both Upper and Lower Limestones occur in a highly altered condition, the carbonic acid having been completely expelled with the production of various crystalline silicates, which are, naturally, minerals rich in lime. The Lower Limestone may be found, with some difficulty, in two small "sikes" west of the farm, and was discovered here by Profs. Harkness and Nicholson, who recognized it as a metamorphosed limestone containing idocrase. The Upper Limestone, though much better exposed, and close to the farm-road, seems to have escaped notice. It is to be observed that the uppermost and purest beds are not seen in this section, which shows only part of the Calcareous Breccia and a few feet of the overlying strata. The small part of the Lower Limestone that is accessible also seems not to belong to the most purely calcareous portion; and, indeed, in both limestones the presence of various aluminous silicates points to some original admixture of earthy or ashy material, as well as the possible intro-

duction of silica in connexion with the metamorphism. None of the altered calcareous strata can be followed for more than about fifty yards along their strike, and the exposures, which are all within 300 yards of the granite-boundary, show complete metamorphism in every case. The next appearance of the Calcareous Breccia towards Great Yarlside, about three-quarters of a mile from the granite, shows little or no alteration. As the limited nature of the exposures thus precludes any attempt to trace the gradual changes in particular beds, we shall content ourselves with describing the constitution of the chief types of metamorphosed limestones found in the sections mentioned.

Beginning with the representative of the Lower Limestone, the most interesting type to be noticed is that consisting mainly of idocrase with lime-garnets and other lime-bearing silicates. In hand-specimens the idocrase is often seen to compose the bulk of the rock, and is readily identified by its light-brown colour, rather imperfect cleavage, and resinous lustre. It forms a framework in which the garnets, &c. are embedded, and usually presents no crystal-outline, nor does it then show the concentric shell-structure found in many idocrases. The specific gravity of a typical specimen of the rock was found to be 3·476, which answers to idocrase with a smaller quantity of lime-garnet. In some parts of the rock the idocrase shows crystal-boundaries, viz. the prism (m), pyramid (y), and basal (c) *.

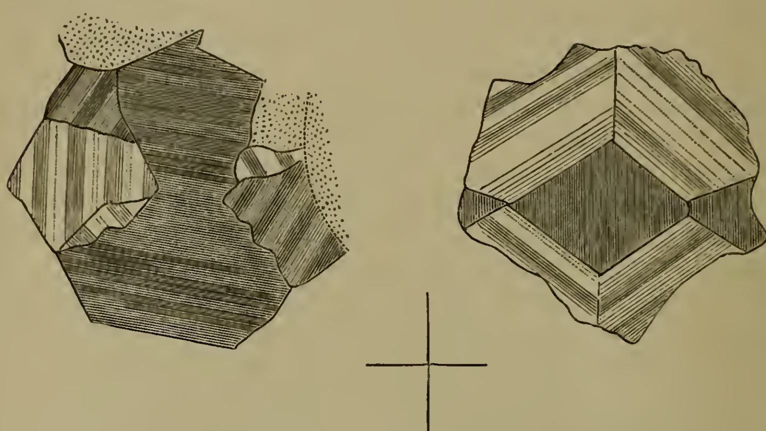
In thin sections the idocrase appears as large shapeless plates enclosing the garnets and other constituents in ophitic fashion, and, as is often the case in minerals having this mode of occurrence, the cleavage-cracks are not well developed (see Pl. XII. fig. 1). The mineral gives bright polarization-tints, which vary slightly in different parts of a crystal. Idocrase is usually stated to give very low tints: Rosenbusch says that the birefringence rarely exceeds ·0015; Michel-Lévy and Lacroix give ·0015 as the mean and, apparently, ·002 as the maximum. Prof. Brögger, however, found brightly polarizing idocrase in the metamorphosed calcareous rocks of the Christiania district, and a slice [1042] of the Monzoni idocrase shows the same character. The idocrase of our rock contains numerous inclusions, mostly minute granules of pyroxene (?), and sometimes crowds of little needle-shaped crystals which we have not identified [1169].

The garnets occur in dodecahedra, up to $\frac{1}{4}$ or sometimes $\frac{1}{2}$ inch in diameter, which are often isolated in the exposed outcrop of the rock, owing to weathering. The crystals have lustrous faces, with the somewhat greenish-yellow colour common in the lime-alumina-garnets (grossularite). In thin slices the mineral shows some interesting features. It is seen to be birefringent, and to present in

* Mr. W. M. Hutchings informs us that he has measured one of these crystals on the goniometer. He finds the angle between the basal plane (c) and the unit pyramid (y) to be between 37° and 38°. Miller gives, for idocrase, 37° 7'. Mr. Hutchings also states that the optical properties are those of normal idocrase.

each crystal a division into several distinct "fields" with different optical orientation. In addition to this there is a zonary banding in polarized light, owing to the successive concentric shells of the crystal differing in amount of double refraction. (See fig. 5.)

Fig. 5.—[1211]. *Doubly-refracting lime-garnets in the idocrase-garnet-rock, metamorphosed Lower Coniston Limestone, of Wasdale Head.*



Drawn in polarized light to show the polysynthetic structure and zonary banding. The + indicates the position of the crossed nicols. Included granules of pyroxene, &c. are omitted for the sake of distinctness.

The existence of optical anomalies in the garnets of the *Kalksilicathornfelsen* has long been recognized. The property of double refraction seems to be constantly accompanied by polysynthetic twinning and a more or less pronounced zonary banding. Klein has distinguished four different types of structure in the doubly refracting garnets. Those of Wasdale Head belong, so far as our observations go, to his *Rhombendodekaëdertypus*, which is defined as built up by twelve hemimorphic rhombic pyramids, each having its base on a face of the rhombic dodecahedron and its apex at the centre of the crystal. The appearances actually seen in slices of the rock of course vary considerably, according to the direction in which each individual crystal chances to be cut. Rosenbusch * states that the type of structure in question is by much the most common in the doubly-refracting garnets, and gives an excellent figure in illustration of it. In our specimens the division between the several individuals of the polysynthetic twin is often rather irregular. The zonary banding is usually, but not always, well marked. None of the zones are isotropic, but the birefringence varies considerably from zone to zone and is negative in character. When strongest, it is about equal to that of quartz: only in rather thick slices do the interference-tints rise to the yellow of the first order. Doubly-refracting garnets, though not confined to metamorphosed limestones,

* 'Mikr. Physiogr. d. petrogr. wicht. Miner.' 2nd ed. (1885) p. 264, and pl. xiv. fig. 2.

appear from the accounts of different writers to be very characteristic of such rocks. Another British example is afforded by the Carboniferous calcareous shales in contact with the large dyke at Plas Newydd on the Menai Straits. The garnets at that locality have a zonary structure, and show the same type of polysynthetic grouping as those of the Wasdale Head rock [149].

In the most common type of the metamorphosed Lower Limestone, doubly-refracting garnet and idocrase build most of the mass. Among other minerals met with are pyroxenes similar to those to be described in the Upper Limestone. A colourless augite is the most common, and is evidently the same as that described below. It is sometimes abundant in crystalline patches showing augite-cleavage and even twinning [1207], and the minute granules, giving bright polarization-tints, which often crowd both garnet and idocrase are perhaps the same mineral. These little granules have the rounded or "globulitic" appearance which has been commented on by Prof. Brögger in similar rocks in Norway.

Another mineral not infrequently found is tremolite, which forms little veins and patches, and encloses imperfect crystals of light-brown sphene [1170]. Anorthite is sometimes to be identified. Quartz apparently does not occur, except in narrow veins evidently representing little cracks.

Another type met with in the altered Lower Limestone shows in hand-specimens a dull-white ground studded with round light-brown spots, up to about $\frac{1}{10}$ inch in diameter, and more irregular pinkish-brown patches of similar size. The round spots are garnets, which in slices are found to be isotropic, and the less regular patches are evidently imperfectly-separated crystals of the same mineral. Both contain a large amount of enclosed material similar to their matrix, which seems to be usually a very finely granular aggregate of wollastonite, augite, &c. [951]. It may be noted that these isotropic garnets are of a browner colour than the doubly-refracting ones (essonite); but there is no reason to suppose that the isotropic character is connected with chemical composition. The isotropic garnets are never in such perfect crystals as the others, and often seem to have been arrested in an incomplete state of development.

The metamorphosed representative of the Upper Limestone is a compact porcellanous-looking rock of pale bluish-grey or greenish-grey colour, closely comparable with lime-silicate hornstones from the Harz and other regions. On closer examination, it often shows a rather mottled appearance on a small scale, some parts being greenish and giving evident indication of crystalline structure. The lower beds, representing the Calcareous Breccia, enclose numerous angular, subangular, and rounded fragments similar to those seen in the unaltered strata in Blea Beck. Some of these fragments are of dark colour and dull appearance, but the majority have a grey horny aspect, and are at once recognized as the usual rhyolite-fragments of these beds, though they appear to have suffered some metamorphism, and their boundary against the enclosing matrix is not always perfectly sharp.

A common feature, which is also seen in the metamorphosed Lower Limestone, is the occurrence of little ovoid or irregular nests, a quarter of an inch to an inch in diameter, of little greenish or light brown crystals, which radiate not from the centre but from one end of the nest. These little aggregates, which consist of a monoclinic pyroxene mineral presumably an augite rich in lime, may perhaps represent original nodular patches more purely calcareous than the rest of the rock. The mineral seems to be identical with one already mentioned as an occasional constituent of the metamorphosed andesites. In the little nodules it is usually bordered by a zone of small felspar crystals (see Pl. XII. fig. 2).

The rhyolite fragments in the metamorphosed Calcareous Breccia appear, in some instances, to have been altered by silicification prior to the metamorphism, but others preserve the cryptocrystalline, microspherulitic, and other structures proper to them. Some are traversed by curving perlitic cracks, now occupied by minute veins of quartz or sometimes pyroxene. This latter appearance is beautifully shown in polarized light, and is clearly due to the cracks having been filled by minute calcite-veins, subsequently metamorphosed into a lime-silicate [1043].

Besides these fragments, there are often little round areas of clear quartz, sometimes consisting of an irregular mosaic. These correspond to the rolled grains of clastic origin seen in the non-metamorphosed rocks, but the quartz has apparently been recrystallized *in situ* [909 &c.].

The matrix in which the fragments are embedded is seen under the microscope to consist of a densely packed aggregate of various crystalline silicates, in which a few are sometimes developed in larger crystals, mostly of very imperfect outline and arranged in tuft-like groupings. The higher beds of the limestone have the same general character.

One common mineral is a colourless, brilliantly polarizing amphibole, which may be referred to tremolite. Cross-sections show the prismatic hornblende-cleavage, and longitudinal sections give extinction-angles up to about 16°. The transverse parting seen in the tremolite of some metamorphosed limestones, *e. g.* in Glen Tilt, Perthshire [1174], is not found here. The mineral sometimes occurs in vein-like streaks or fan-like tufts [909]; at other times it makes up almost the whole of the rock in particular spots [1215], see Pl. XII. fig. 3. The abundance of tremolite and other magnesian minerals in these altered rocks, sometimes to the exclusion of simply lime-bearing silicates like wollastonite, suggests that the limestone may have been partly dolomitized before its metamorphism.

Two pyroxene minerals are recognizable in the rock, often associated in the same slide, building little crystalline grains and minute granules. One of these, with a scarcely perceptible yellow tinge in the slices, has the augite-cleavage and gives in longitudinal sections a maximum extinction-angle of about 40°. Its other properties are those of the augites, and, being doubtless a variety rich in lime, it

may be termed "lime-augite." It is evidently the mineral which gives the greenish tint to hand-specimens of the rock, and is apparently identical with the pyroxene which occasionally occurs in the metamorphosed andesites. It is usually a conspicuous element in slices of the altered Upper Limestone and Calcareous Breccia (see Pl. XII. fig. 4).

The other pyroxene, completely colourless in the sections, has a considerably lower refractive index and rather less double refraction. Sections showing one marked set of cleavage-traces extinguish parallel to these traces. Taking account of all its properties, this mineral may be referred with some confidence to wollastonite. It is less abundant than the augite, and does not occur in larger crystals such as those in the radiating nests and tufts of the latter mineral. In some slides it is the dominant pyroxene [872], in others it occurs in smaller quantity associated with the augite [874].

We have not found garnet in the metamorphosed Upper Limestone. A mineral probably referable to idocrase (?) occurs in one or two slides [1217], but never in the abundance which characterizes the metamorphosed Lower Limestone. Felspar is a common constituent, in groups of irregular crystal-grains or occasionally in ophitic plates moulding the augite, &c. It has the water-clear appearance common to the authigenetic felspars of all these metamorphosed rocks, and the crystals are more commonly simple than twinned. Judging by extinction-angles observed in the twinned crystals, both acid and basic felspars occur: some are certainly to be referred to anorthite. Quartz seems to be present only sparingly in these rocks, but in the very fine-grained parts it is not easy to discriminate between this mineral and felspar, and the analysis given below proves that a certain amount of free silica is present. Some slides of the Calcareous Breccia contain a considerable amount of brown mica, usually in small flakes of a pale colour [1214, 1215, 1216], and there are some little veins of pale yellow pleochroic mica with clear quartz [1213]. A grain or two of magnetite is seen only very rarely [874].

It will be seen from the above brief account that the Wasdale Head section affords some interesting examples of highly-metamorphosed calcareous rocks. The beds here exposed have evidently not, for the most part, been of the nature of pure limestones. The considerable amount of alumina represented by the garnets and idocrase in the "Lower Coniston Limestone" at this locality clearly points to the former abundance of ashy material in the strata; they were probably calcareous shales or fine ashes, like those which are seen at Stile End and constitute the usual *facies* of this subdivision. The Upper Limestone, in so far as it is represented at this spot, must also have been impure, and was probably to some extent dolomitized. Indeed, Mr. Garwood finds these porcellanous-looking rocks to be rich in magnesia as well as in lime. The following analysis of an average specimen of the metamorphosed Upper Limestone probably gives a fair idea of the constitution of the altered rocks of this divi-

sion (I.). We give for comparison an analysis of a similar rock from the Christiania district (II.) :—

	I.	II.
SiO_2	55·45	57·43
TiO_2 and ZrO_2	...	1·13
X (unknown)	...	0·12
CO_2	0·00	0·00
P_2O_5	...	trace
Cl	...	trace
Al_2O_3	15·91	17·53
Fe_2O_3	6·84	0·00
FeO	not estim.	1·76
MgO	3·65	1·47
SrO	...	trace
CaO	11·50	8·51
Na_2O	0·10	1·76
K_2O	3·36	8·51
Li_2O	...	trace
H_2O	...	1·05
FeS_2	...	0·77
Ignition	...	(1·30)
	96·81	100·04
Specific gravity	2·712	2·741

I. Metamorphosed Upper Coniston Limestone, Wasdale Head Farm; anal. E. J. Garwood.

II. Pale violet *Kalkhornfels*, Gunildrud, near Christiania; anal. Jannasch, Nyt Mag. Naturvidensk. vol. xxx. p. 303.

The notable percentage of potash in our rock (though less than in the Norwegian one) must have come from ashy material in the original beds, and the alumina points to the same fact. The potash now exists in the abundant orthoclase of the rock: the percentage of alumina is evidently too high to be contained in the felspars alone; part of it must be combined in the pyroxene. A rough calculation shows that the amount of quartz in the rock must be about 19 per cent. If we suppose that the rock has undergone no change of total chemical composition beyond the loss of carbonic acid, and that the whole of the lime and magnesia originally existed in the form of carbonates, we find that silica must have formed about 50 per cent. of the original rock, or excluding the calcite and dolomite, 67 per cent. This figure does not seem too high, if, as we believe, the non-calcareous part of the rock was chiefly ashy material of rhyolitic character, with a little clastic quartz in addition. The analysis does not, therefore, prove that silica has been introduced during the metamorphism.

The phenomena of metamorphism exhibited by the Wasdale Head rocks agree in many particulars with those that have been described in impure calcareous strata near other intrusive masses, such as the Ramberg granite in the Harz *, and the hornblende-

* Lossen, 'Erläut. zur geol. Specialk. v. Preussen' (1882), Blatt Harzgerode, pp. 66–73.

granite of Eker and Sandsvär, near Christiania *. English geologists who have read the masterly memoirs of Lossen, Brögger, and Lang will be interested to learn that many of the phenomena described by the Continental petrologists may be studied in our own country. The metamorphism near the Shap Fell granite is as complete as any described in similar strata, the rocks being entirely reconstituted with expulsion of the whole of the carbonic acid.

D. *The Silurian Rocks.*

Owing to a strike-fault, which has already been alluded to, the lowest members of the Silurian are not seen in our district. The next set of rocks to be noticed is the Lower Coniston Flags or Brathay Flags, which are well exposed, and can be traced to within about 350 yards of the granite. There is little doubt that these strata are in contact with the intrusive rock along its southern boundary, but this junction and the inner ring of the aureole of metamorphism are concealed by superficial accumulations. For this reason, and in view of the numerous descriptions of metamorphosed argillaceous rocks already given by various writers, it will not be necessary to treat the rocks in question at great length. We shall confine ourselves chiefly to following the stages of alteration exhibited by the rocks exposed along the banks of Wasdale Beck. As the line thus traversed coincides very closely with the strike of the beds, we need not expect to find any variations other than those due to varying degrees of metamorphism.

The exposure nearest to the Hotel is about 1400 yards from the granite outcrop as laid down on the map, and here the metamorphism is very slight. It consists in a certain hardening of the rocks and a partial loss of the fissile character, though both bedding and cleavage are still easily made out. The flags here have a dull black colour, due no doubt to organic material, and they contain recognizable graptolites. The specific gravity is 2·7645. A slice [863] from this locality shows abundance of carbonaceous matter, mainly arranged along the direction of lamination, which is crossed at an acute angle by cleavage. There are also minute angular grains of quartz. These constituents are embedded in a mass of finely-divided dusty matter, such as might arise from decomposed felspathic fragments, with a certain amount of quartz-cement. The specimen does not differ materially from the Brathay Flags of Stockdale [1284].

Following the rocks up the beck, we observe that from dark they become yellowish-grey in colour, but with countless little black spots which take on the lustre of mica. The spots are seen as far as the flags can be traced, that is, within about 350 yards of the granite. A specimen here has a specific gravity of 2·732, which is lower than that of the less altered rock.

A microscopic examination of the specimens shows that the outer

* Brögger, 'Die silurischen Etagen II. und III. im Kristianiagebiet' (1882); see also Lang, Nyt Mag. Naturvidensk. vol. xxx. pp. 335 *et seqq.*

limit of the aureole of mineralogical metamorphism is rather sharply defined. While the flags seen nearest the Hotel have undergone no important alteration, specimens at no great distance from them, and about 1220 yards from the granite-boundary, show very considerable modifications. The carbonaceous matter has been entirely dissipated by "ignition," unless indeed it be partly represented by some of the black granules scattered through the rock. We cannot be sure that some of these are not graphite, and the flaky form of many of them renders it probable; but others are certainly magnetite, and by their tendency to crystal outline suggest a metamorphic origin. The chief authigenetic mineral, however, is brown mica, which is disseminated in minute flakes throughout the whole mass of the rock. The character of the ground, showing very minute granules of quartz and apparently felspar, is more evident; but this may be due rather to the removal of the opaque organic matter than to any real change in the other constituents. The more easily visible angular grains of clastic quartz, at least, have remained unaltered [1221].

Nearer to the granite (at 870 yards) the brown mica forms flakes slightly larger and more distinct, while the general ground of the rock gives clear evidence of recrystallization. In the little streaks where this is best seen, there is a fine-grained aggregate of grains which may include felspar as well as quartz, and the authigenetic character of this aggregate is sufficiently proved by its mosaic arrangement, its limpid appearance, and especially the manner in which it moulds and encloses the mica. In other parts of the slide the nature of the very fine-grained mass, obscured by the mica, is not to be made out with certainty [1220]. There are still evident angular quartz-grains of detrital origin. The opaque grains belong to a yellow pyrites-mineral which seems to be pyrrhotite.

[We are indebted to the kindness of Mr. W. Maynard Hutchings for drawing our attention to the occurrence of anatase in a specimen from Wasdale Beck. The mineral occurs in groups of very minute crystals in the clearer spaces of the rock, and is conspicuous under a high power by its very high refractive index and birefringence [1327]. Owing probably to the total-reflection border, the crystal form is seen in only a few of the crystals. It appears to be the simple pyramid, or but slightly modified. The straight extinction and the character of the double refraction ($\omega > \epsilon$) agree with anatase, and there is but little doubt of the identity of the mineral. Further, it seems to be formed at the expense of rutile, for Mr. Hutchings points out that the "clayslate-needles," which he finds in the less metamorphosed flags lower down the beck, are here almost absent. The locality of the specimen is apparently about 800 or 900 yards from the granite-outcrop.—March 11th, 1891.]

Still approaching the granite, we come on to the spotted or "knotted" rocks. A specimen taken at 500 yards from the contact does not materially differ, except as to the spots, from the last, the recrystallized mosaic, in which some rectangular sections clearly point to felspar, being visible only in some portions of the slide, while the

rest is very obscure. The rather irregular spots, $\frac{1}{50}$ to $\frac{1}{20}$ inch in diameter, are differentiated by their comparative freedom from mica [1219].

At 360 yards from the granite the spots are more regularly ovoid and their boundary more sharply defined, the brown mica in the interspaces forming distinct small flakes arranged tangentially to the outlines. The central part of each spot contains smaller flakes, often rather rounded, but the marginal zone is free from mica [1218]. (See Pl. XII. fig. 5). In some specimens from this neighbourhood the mica in the general body of the rock has a marked parallel arrangement, which corresponds to the lamination of the original flags [864].

An example from Packhouse Hill has less mica, and that of a pale colour, but here pyrrhotite is exceptionally plentiful, and has presumably used up most of the iron which has elsewhere gone into the usual brown pleochroic mica [1222]. This is at 600 yards from the granite. A specimen from Collyrag Quarry, a hundred yards nearer, shows similar characters [1079]. These rocks are on a slightly higher horizon than the preceding. They show little or no indication of "spots," have rather abundant clastic quartz, and present a considerable resemblance to the Upper Coldwell beds exposed farther south.

The normal brown mica of the metamorphosed flags resembles in general characters that which has been produced in the andesitic and other rocks described above. Such mica has a special quality as seen in reflected light, which gives a peculiar purplish-brown sheen to the rocks in which it is abundant. With this goes a very intense pleochroism in thin sections, the absorption being almost complete for vibrations parallel to the cleavage-traces, while, if the nicol be turned a very little away from this position, a distinctly greenish-brown colour is seen. Similar characters have been described by various writers in the mica of "contact" rocks in other districts, and it would be interesting to ascertain whether the mineral is chemically different from the brown micas of igneous rocks. The only investigation we can find on this point is in Lang's brilliant paper on the Christiania district, already referred to above. He and Jannasch separated and carefully analysed the brown mica of a *Glimmerhornfels* in that district. They found it to contain 7·98 per cent. of magnesia and 21·94 of ferrous oxide, ferric oxide being entirely absent: also titanic acid occurs to the extent of 3·40 per cent *. Except for the absence of ferric oxide the figures differ but little from Schläpfer's analysis of the biotite of Miask. The last-named author has shown that the earlier analyses of micas leave much to be desired in point of accuracy.

The nature of the "spots" in such rocks as these is not an easy question, and it seems clear from the literature of the subject that the phenomena of spotted and knotted slate-rocks arise in several different ways. We find nothing of the local accumulation of the "pigment" of the rock into spots, which characterizes the

* *Op. cit.* p. 318.

outer ring of metamorphism (*Knotenthonschiefer*) in some districts of argillaceous strata, such as Rosenbusch's * *Steiger Schiefer*. The spots in our rocks are comparatively free from coloured constituents, and do not make their appearance until after considerable development of secondary minerals. The original pigment of organic matter is dissipated as the first result of metamorphism. Moreover, the spots in the Brathay Flags, when best developed, show a distinctly crystalline structure between crossed nicols, being evidently imperfect crystals charged with a large quantity of foreign inclusions. The ovoid form seems to be that of imperfectly formed crystals, for the general ground of each spot extinguishes parallel to the long axis of the irregular oval, which has no universal direction, but lies quite at random. Possibly the mineral may be andalusite.

Apart from the spots, it will be noticed that andalusite is absent, as well as other characteristic aluminous "contact-minerals." It would appear that the rock contained sufficient alkalies to build up a large part of the alumina present into secondary felspars.

The veins of white mica have already been mentioned. The rock adjacent to these shows some curious modifications, being built in great measure of a clear colourless mica similar to that occupying the veins [949, 1080]. This mica is partly in minutely-matted aggregates, but mostly in well-defined flakes with rough parallelism, moulded by a clear crystalline mass of grains, some of which show felspar-twinning. The brilliantly polarizing flakes are also moulded by another micaceous-looking mineral with a very pale greenish-grey colour and feeble dichroism, but not sensibly birefringent. This may be one of the ripidolite group, but we have not established its identity with any described variety. A little magnetite and granules of the supposed pyrrhotite occur. Brown mica is only sparingly associated with the white in this marginal modification of the rock. At about an inch from the actual vein, however, the spotted character of the rock is apparent, and brown mica occurs as usual in the interspaces between the spots. There is still a considerable amount of white mica, mostly in exceedingly minute scales within the spots, but partly in more conspicuous flakes near their margin. One slide [949] shows a crack running at right angles to the main vein, its course marked by a slightly coarser aggregate of colourless mica and quartz, with some clear felspar, a little of the ripidolite-like mineral, and occasional grains of yellow-brown tourmaline, touched here and there with blue.

Of the remaining members of the Silurian formation we have made no systematic examination, but the few specimens studied offer some points worth recording. The Upper Coldwell beds and the less calcareous portion of the Middle Coldwell, viz. the lowest strata of that division exposed at Packhouse Hill, bear a general resemblance to the uppermost beds of the Brathay Flags at the same locality, and the resemblance is borne out by the microscope. Numerous minute shreds of a mineral like tremolite disseminated through these metamorphosed flags perhaps point to a certain

* 'Abh. zur geol. Specialk. v. Elsass-Lothr.' vol. i. (1877) part 2.

amount of carbonates of lime and magnesia in the original rock. The metamorphism is evidently incomplete, and the clastic grains of quartz show no change.

The Coniston Grit and the Lower Coldwell beds (or grits in the Coniston Flags) resemble one another very closely. They are ordinary grauwacke grits. A specimen of the former, taken near Stakeley Folds, shows in a section subangular grains of quartz and felspar with some interstitial dusty matter like kaolin, and little patches of finely granular calcite. The felspar has minute twin-lamellation and is rather abundant, though subordinate to the quartz. There is no other clastic element except very rarely a flake of white mica. The rock is freely veined with quartz [1165].

For comparison we take a specimen of the Lower Coldwell grit at Packhouse Hill, about 600 yards from the granite-contact. The contrast is evident in hand-specimens, the metamorphosed rock showing the vitreous appearance of a quartzite, in which the granular structure is only faintly discerned. Under the microscope [1223] we see a mosaic of quartz and felspar, the irregular grains of which show the "sutural" junction characteristic of crystallization *in situ*. It is not easy to judge of the proportion of felspar present, since the grains are all perfectly clear, and twinning is rarely seen. The twinning is never compound, and the grains showing it give rather lower polarization-colours than the average, which seems to point to orthoclase. Besides these minerals there are numerous little rounded brightly-polarizing granules, colourless or very faint yellow, and precisely similar to those so commonly seen in the metamorphosed Coniston Limestones. We regard these as a lime-augite. The granules are aggregated together, especially in irregular vein-like streaks. The slide shows also some small irregularly-shaped granular patches, so densely packed as to be opaque, and appearing yellow in reflected light. These are, at least in part, of the same pyroxenic mineral, which corresponds closely in its distribution with the calcareous decomposition-product in the non-metamorphosed grit. It is noteworthy that neither mica nor garnet has been found. The kaolin seems to have gone with the carbonates to form pyroxene. (See Pl. XII. fig. 6.)

The quartz in this rock encloses many irregularly-grouped minute cavities, round or more frequently shapeless, with bubbles of various relative size. Judging by the apparent relief of cavities and bubbles, both glass- and fluid-pores may be represented, but no movement was verified in any of the bubbles.

The calcareous Middle Coldwell beds, as seen on the top of Packhouse Hill, exhibit a high degree of metamorphism. As in the Coniston Limestone, this is shown especially by the development of lime-bearing silicates, and, although we have no analyses of these Silurian strata, a comparison with the general character of the unaltered beds makes it appear that a very moderate proportion of calcareous matter, which would not cause a field-geologist to describe the rocks as limestones, is sufficient to make the metamorphism follow this line.

Probably more than one lime-silicate is present. The dominant one gives the interference-colours of a pyroxene, and has marked cleavage-traces, parallel to which it extinguishes. This may be referred with some doubt to wollastonite. It is partly collected in crystalline patches and streaks, but smaller granules of the same or a similar mineral make up a large part of the rock, in conjunction with a clear substance polarizing in grey tints and occasionally showing the twinning of felspar. In the pyroxenic patches occur grains of a yellow opaque mineral, probably pyrrhotite. Here and there among the pyroxene is seen a little grain of calcite, showing that here, at 600 yards from the granite, the elimination of the carbonic acid is not quite complete [1225].

In hand-specimens this rock has a compact homogeneous appearance, with a pinkish-grey or pale violet colour, and a hardness rather less than that of orthoclase. The specific gravity of an average specimen is 2·874, which agrees with the identification of the chief constituent as wollastonite. The pale violet colour figures frequently in descriptions of foreign lime-silicate rocks.

Specimens of the Middle Coldwells taken at a point S.S.W. of Wasdale Old Bridge show a similar compact porcellanous appearance, but with a light grey colour, They resemble very closely the Upper Coniston Limestone of Wasdale Head, but have a rather higher density, 2·899, owing, as the microscope shows, to a larger proportion of pyroxene. The dominant mineral here is the colourless lime-augite, which is largely developed, in crystal-plates enclosing the felspar, &c. in ophitic fashion [1306, 1307]. At this locality, about 460 yards from the probable outcrop of the granite, there is no longer any trace of calcite remaining. It would appear that, in these impure calcareous rocks, the particular lime-silicates produced vary from point to point, as determined, perhaps, by comparatively slight differences in the chemical composition of the mass. Some light is thrown on the conditions governing the formation of augite, wollastonite, &c., by Vogt's * interesting researches on slags.

An interesting feature in the Packhouse Hill section is a metamorphosed fault-breccia, which intervenes between the Lower and Middle Coldwell beds. The lowest beds seen here in the Middle division are ordinary flags, but there appears to have been a lower calcareous band similar to that described above, for fragments of the characteristic pale-violet rock occur in the breccia, mingled with pieces of the dark flags and vitrified-looking fragments of the underlying grit. The whole is united by a greenish finely-crystalline cement of pyroxene.

The fragments of grit appear in sections as a mosaic of clear crystal-grains of quartz and felspar, evidently of metamorphic formation. It is impossible to estimate the proportions of the two minerals, but a fair number of the grains show twinning and seem from their properties to be orthoclase. No repeated twinning is observed [1286, 1287]. Among the grains of the mosaic, and

* Arch. f. Math. og Naturvidensk. vol. xiii. (1890) pp. 34–71, Christiania.

enclosed by them, are patches of rounded granules, highly refringent and birefringent, which must be referred to a pyroxene, probably the lime-augite already frequently alluded to. These granules are mainly collected at the margin of the fragments or in the neighbourhood of little vein-like cracks.

The angular pieces of flag show a marked lamination defined by streaks of opaque dust. Their metamorphism is similar to that of the corresponding rocks *in situ*, except where the fragments are traversed by cracks and veinlets, which evidently represent a permeation by carbonate of lime and other substances. In these places a number of special minerals may be detected, lime-silicates predominating. The usual colourless augite is abundant in irregular crystalline patches, often accompanied by clear felspar and probably quartz. There are also streaks composed entirely of a minutely matted aggregate of rather fibrous tremolite [1285]. Near these there is frequently a pale yellow-brown pleochroic mica, in clusters of small flakes. A pyrites mineral occurs among the tremolite and felspar, and by its colour would be assigned to pyrrhotite.

The metamorphosed fragments of the more calcareous flags in the breccia generally show a finely granular mass, mostly polarizing in bright tints, but too minute to be precisely determined. The general character of the mass may, however, be inferred from those constituents which are here and there developed in larger crystalline patches. Of these the most usual is colourless augite, readily identified by its cleavage, extinction-angles, and interference-colours. Another conspicuous mineral is light brown, pleochroic sphene, which occurs plentifully in grains and good crystals (habit, n, c, y) scattered through the fragments.

The cementing material of the breccia is almost exclusively colourless augite, building a relatively coarse-grained crystalline aggregate, and enclosing plenty of little sphene crystals [1286]. This cement makes up on the whole a small part of the mass, and it, with the smaller veins traversing the fragments, clearly represents a calcareous infiltration filling the interstices of the original fault-breccia. No calcite now remains.

In conclusion we may note one or two points with reference to the metamorphism of the Shap Fell rocks as a whole. The production of new minerals is confined to distances of not much more than 1200 or 1300 yards from the granite-contact, or about equal to the mean semidiameter of the intrusive mass itself as exposed at the surface. The width of the metamorphic aureole, as thus defined, seems to be tolerably uniform in different directions from the granite. Moreover, this extreme limit of metamorphic action is very nearly the same, whether we consider the andesitic rocks, the rhyolitic ashes, the various calcareous strata, or the Brathay Flags.

Within the metamorphic aureole the changes increase in degree

as we approach the granite, and, with few exceptions, the rocks in the vicinity of the contact have been completely reconstituted. Our results, however, lead to the conclusion that any division of the aureole into distinct rings or zones would be arbitrary and artificial, and certainly could not be made to apply alike to the various kinds of rocks metamorphosed. In the andesites, for example, the transition from the least altered to the most altered types is so gradual that no lines of division can be drawn either in the field or by minute examination. In the rhyolitic ashes our descriptions show two different types, but the distinction of these two would probably resolve itself into one of degree rather than of kind, if it were possible to examine the rocks between 300 and 600 yards from the granite, between which limits we have found no exposures. As to the calcareous beds, these have been described in other districts as showing a very complete alteration to points even beyond the limit of the aureole in the associated slates, though with no gradations in metamorphism within those limits. But, although we find in our calcareous rocks a high degree of metamorphism extending to a considerable distance from the actual contact, this seems, so far as we can judge from the rocks exposed, to die away gradually to the boundary of the aureole. The flags in the Shap district are not well enough exposed to warrant any sweeping conclusions, but it would be difficult to draw any divisional line in those seen within the metamorphic region. Zones of metamorphism may perhaps be usefully laid down in certain cases, as, for instance, when a mineral like chiastolite is developed in the outer part of the aureole and disappears in the inner; but such divisions do not appear practicable in the Shap Fell district.

It is noticeable that the chemical effects of the metamorphism were first produced in those constituents of the rock which owed their origin to weathering, decomposition, &c., such as delessite, calcite, and carbonaceous matter. In other words, the substances which had been formed under normal atmospheric conditions were the least stable when subjected to the high temperature which accompanied the intrusion of the granite. The minerals of direct igneous origin in the volcanic rocks were less susceptible to thermal metamorphism, and the original quartz-sand in the flags proved especially refractory.

The several minerals detected in the various metamorphosed rocks as products of the metamorphism are summarized in the table given below. The absence or rarity of some characteristic "contact-minerals" of other districts is rather striking. Some of these are products which probably require special "mineralizing agents" to co-operate in their manufacture; such as fluorite, tourmaline, lithionite, and axinite; but the almost complete absence of andalusite, staurolite, and garnets (other than lime-garnets) is more remarkable.

In the table the occurrence of the minerals in the different rocks studied is marked by an asterisk (*). Parentheses ( ) indicate rarity or occurrence only under special conditions, *e.g.* in the vicinity

of veins. A query (?) indicates some doubt as to the identity of the mineral. The more doubtful ones, such as the possible andalusite in the spotted flags, are omitted altogether; as are also minerals, like epidote, of which the metamorphic origin is not satisfactorily established.

Table showing the distribution of Minerals of Metamorphic Origin in the chief rocks examined.

Minerals.	Andesites.	Andesitic Ashes.	Rhyolites.	Rhyolitic Ashes.	Lower Limestone.	Upper Limestone.	Brathay Flags.	Mid. Coldwell beds and Fault-Breccia.
Quartz	*	*	*	*	...	*	*	*
Orthoclase	*	*	*	*	...		?	*
Plagioclase (various)	*	*	*	*	*		*	*
Colourless Mica (Muscovite)	...	...	*	*	...	...	*	...
Brown Mica (probably near Biotite)	*	*	*	*	...	*	*	*
Ripidolite?	...	...	...	...	...	...	*	...
Green Hornblende	*	*	...	(*)	...	...	...	...
Actinolite	*	*	...	...	...	...	...	...
Tremolite	...	...	...	...	*	*	...	*
Colourless Augite (probably rich in lime)	*	*	...	(?)	*	*	...	*
Wollastonite	...	...	...	...	*	*	...	*
Idocrase	...	...	...	...	*	?	...	...
Grossularite (birefringent)	(*)	...	...	...	*	...	...	...
Essonite (isotropic)	...	...	...	...	*	...	...	...
Common Garnet	(?)	...	...	...	...	...	(?)	...
Tourmaline	...	...	(*)	...	...	...	(*)	...
Sphene	*	...	...	...	*	...	...	*
Rutile	...	...	...	*	...	...	...	...
Anatase	...	...	...	...	...	...	*	...
Apatite	(*)	...	...	*	...	...	...	...
Cyanite	...	...	...	*	...	...	...	...
Magnetite	*	*	...	*	...	(*)	*	...
Ilmenite	...	...	...	*	...	...	...	...
Pyrites and Pyrrhotite	*	...	*	(*)	...	...	*	*
Graphite	...	...	...	...	...	...	?	...

EXPLANATION OF PLATES X., XI., & XII.

Plate X.

Map illustrating the relations of the Shap Granite and associated rocks.

(*The figures are all drawn in natural light, and, except* Pl. XII. fig. 5, *are magnified* 20 *diameters. The numbers in brackets* [ ] *refer to the slides.*)

Plate XI.

Fig. 1 [902]. Shap Fell granite, normal type; showing clear quartz, turbid felspar, and flakes of brown mica. A flake near the lower right-hand edge contains a small zircon surrounded by a strongly pleochroic border.

Fig. 2 [399]. Dark patch in Shap Fell granite; showing quartz, felspar, and mica, as before, but the last more plentiful; also grains of sphene, octahedra of magnetite, and little needles of apatite. See p. 281.

Fig. 3 [1281]. Special modification of Shap Fell granite, containing andalusite; not found in place. The portion of the slide figured is rich in andalusite, which forms imperfect prismatic crystals, coated with brown mica and enclosing magnetite, zircon, mica, &c. Around some of the inclusions, especially zircons, are pleochroic halos, changing from bright yellow to colourless. The bulk of the rock is a mosaic of felspar and quartz with abundant crystals of magnetite and occasional apatite. See p. 283.

Fig. 4 [1205]. Metamorphosed vesicular andesite, near Wasdale Pike, about 800 yards from the granite. The upper half shows a vein of chalcedony converted into quartz. The lower half shows a vesicle in which the delessite (represented dark for distinctness) has been partly replaced by green hornblende. The clear mineral in the lower part of the vesicle is quartz. This rock represents an early stage of metamorphism. See p. 294.

Fig. 5 [897]. Metamorphosed vesicular andesite, Wasdale Pike, about 500 yards from the granite; showing the groundmass of the rock converted into a fine-grained aggregate of brown mica, felspar, quartz, and magnetite. Within the vesicle is green hornblende instead of mica. A patch of granular sphene is seen at the lower edge of the figure, on the line of a small crack. See p. 296.

Fig. 6 [1203]. Metamorphosed vesicular andesite, north of Wasdale Pike, about 400 yards from the granite; showing an unusual type of alteration, brown mica and felspar (in relatively large crystals) being formed in the interior of the vesicles, as well as in the groundmass. See p. 297.

Plate XII.

Fig. 1 [1169]. Idocrase-garnet-rock in the metamorphosed Lower Coniston Limestone, Wasdale Head, about 100 yards from the granite; showing dodecahedra of grossularite garnet embedded in ophitic crystals of idocrase. Both minerals contain granular pyroxene and other matter, and the idocrase encloses groups of small needle-like crystals. See p. 311.

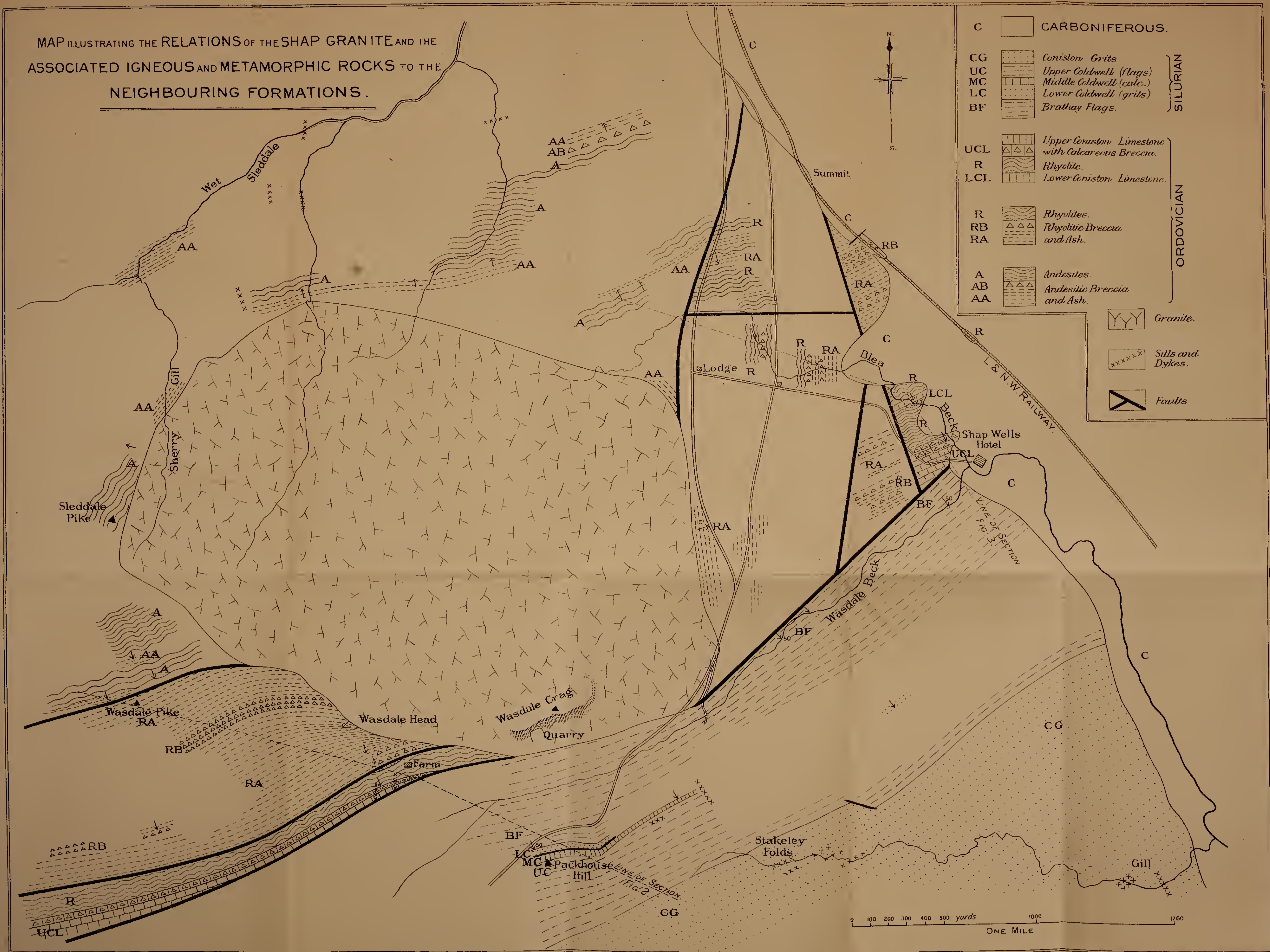
Fig. 2 [909]. Ovoid nest of colourless lime-augite, bordered by a zone of felspar crystals, in the metamorphosed Calcareous Breccia of the Upper Coniston Limestone, Wasdale Head, about 250 yards from the granite. Two quartz grains, of clastic origin, are seen in the lower part of the figure. Flakes of brown mica cluster round these and round the augite-felspar nest. See p. 314.

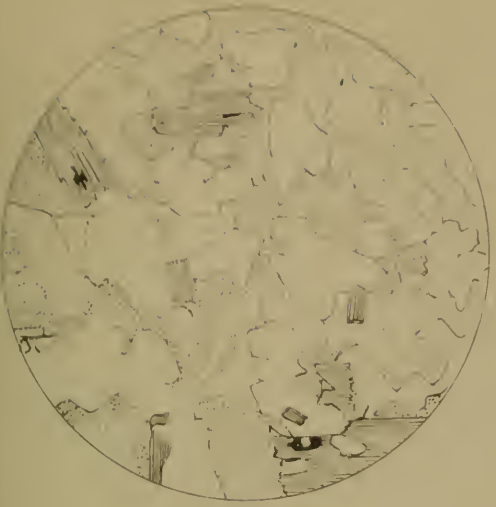
Fig. 3 [1215]. Tremolite-rock in the metamorphosed Calcareous Breccia at the same locality. See p. 314.

RBONIFEROUS.

ston Grits
r Coldwell (flags)
lle Coldwell (calc.)
er Coldwell (grits)
hay Flags.

SILURIAN


MAP ILLUSTRATING THE RELATIONS OF THE SHAP GRANITE AND THE ASSOCIATED IGNEOUS AND METAMORPHIC ROCKS TO THE NEIGHBOURING FORMATIONS.
C CARBONIFEROUS.
CG Coniston Grits
UC Upper Coldwell (flags)
MC Middle Coldwell (calc.)
LC Lower Coldwell (grits)
BF Brathay Flags.
SILURIAN
UCL Upper Coniston Limestone with Calcareous Breccia.
R Rhyolite.
LCL Lower Coniston Limestone.
R Rhyolites.
RB Rhyolitic Breccia
RA and Ash.
A Andesites.
AB Andesitic Breccia
AA and Ash.
ORDOVICIAN
Granite.
Sills and Dykes.
Faults
N.
S.
Wet Sleddale
Sherry Gill
Sleddale Pike
Summit.
Lodge
Blea Beck
L. & N.W. RAILWAY
Shap Wells Hotel
Wasdale Beck
LINE OF SECTION FIG. 3
Wasdale Pike
Wasdale Head
Wasdale Crag
Quarry
Farm
Packhouse Hill
LINE OF SECTION FIG. 2
Stakeley Folds
Gill
0 100 200 300 400 500 yards 1000 1760
ONE MILE



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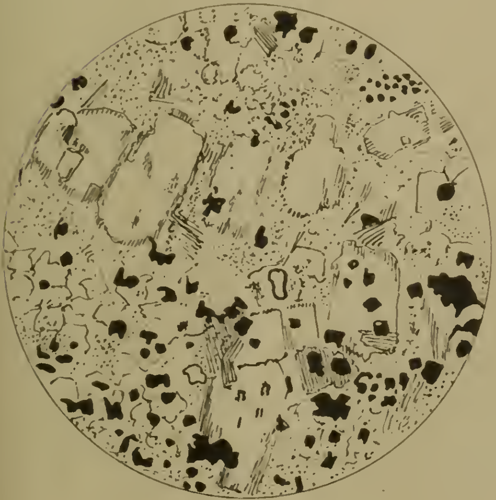

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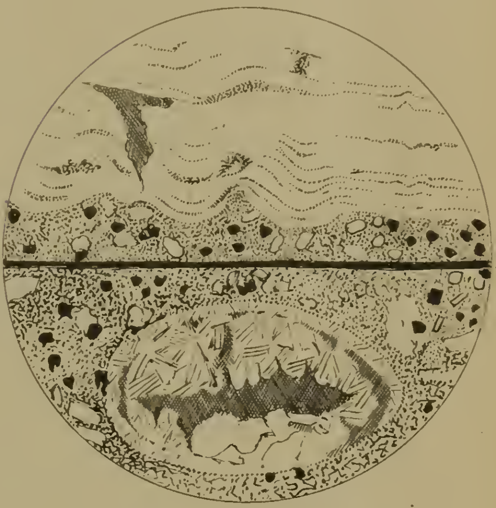

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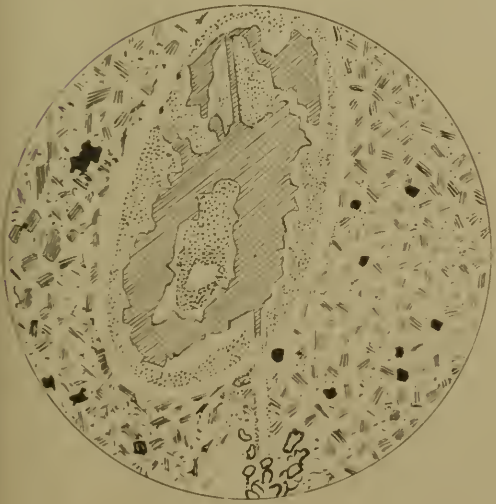

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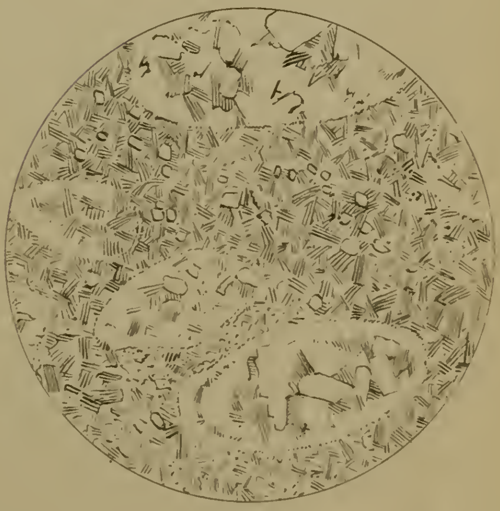

6.

A. Harker del. Mintern Bros. lith.

SECTIONS OF SHAP GRANITE AND METAMORPHOSED ANDESITES.

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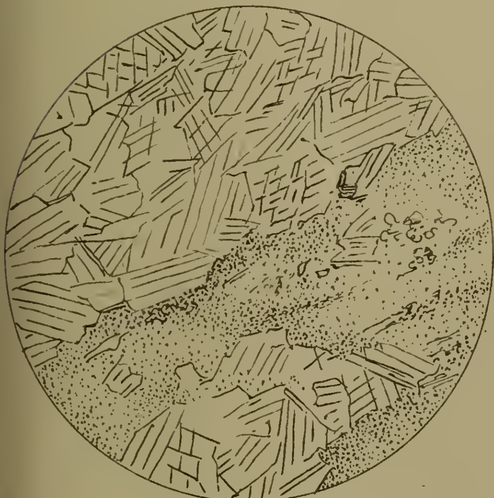

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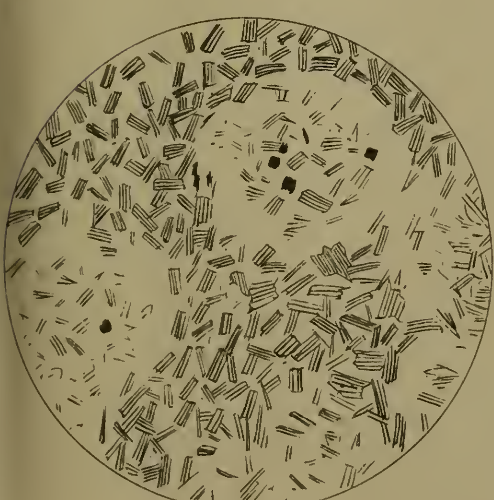

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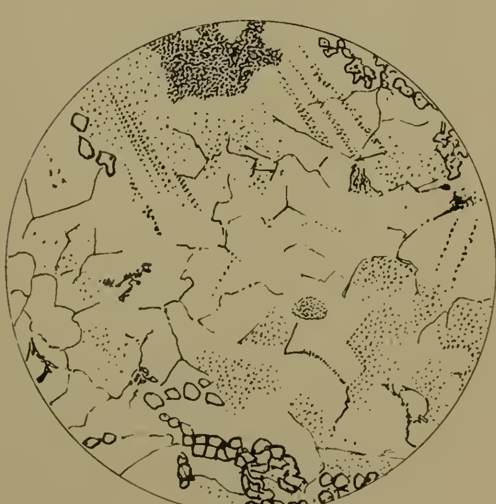

6.

A. Harker del. Mintern Bros. lith.

SECTIONS OF METAMORPHOSED ROCKS NEAR THE SHAP GRANITE.

Fig. 4 [873]. Lime-augite-rock in the metamorphosed Upper Coniston Limestone at the same locality; showing colourless augite, both in crystalline aggregates with good cleavage and in granules and granular patches. See pp. 314–315.

Fig. 5 [1218]. Spotted schist in the metamorphosed Brathay Flags, north of Wasdale Beck, about 360 yards from the granite; showing little spots comparatively free from the secondary brown mica. This figure is magnified 100 diameters. See p. 319.

Fig. 6 [1223]. Quartzite, with colourless lime-augite, in the metamorphosed Lower Coldwell beds (grits) just north of Packhouse Hill, about 580 yards from the granite. The pyroxene occurs in distinct rounded granules and in finely granular patches. See p. 321.

Discussion.

Prof. Bonney said that it was almost impossible to discuss a paper of such wide bearings, but it appeared to him to be one of great value. The most important points were the clear demonstration of the occurrence of felspar as a product of contact-metamorphism, and the effects of the intrusion of an igneous mass on pyroclastic rocks. He mentioned some cases which illustrated the uncertainty as to what mineral might be produced by contact-metamorphism.

Prof. Le Neve Foster said that the point which struck him as a miner, with reference to the intrusive boss of granite, was the absence of tin-ore. The Authors had remarked that no axinite or fluorspar had been found, and that tourmaline was very rare. It was interesting to note that where there was a lack of minerals containing boron and fluorine there was a complete absence of cassiterite.

Mr. Strahan asked for an explanation of the connexion referred to between the intrusion of the granite and the Pennine movements, by which were usually meant post-Carboniferous movements. The map exhibited of a necessity showed the dykes in a diagrammatic form. He enquired if this radial arrangement with reference to the granite would appear if they were shown on a true scale. In the Cautley neighbourhood micro-granites of the same age as the Shap granite occurred as sills in Coniston Limestone, and were cut across by mica-trap dykes, which seemed to show that the more basic rock was later than the more acid, and not earlier as argued from inclusions in the Shap granite.

Mr. Rutley thought that the red felstone-like dykes (often more or less micaceous) were probably apophyses of the Shap granite, as indicated by the Authors. With regard to the dark micaceous dykes being in any way related to the highly micaceous inclusions met with in the granite, he felt considerable doubt. Judging from the alterations produced artificially in rhyolitic rocks by heat, he was inclined to believe that the temperature under which the alterations in the rhyolites had been effected in the Shap area was a comparatively low one. The occurrence of the peculiar polysynthetic structure in the garnets which the Authors described was, he believed, the first notice of such a structure in British garnets, since, hitherto, it had only been observed in ouwarowite and in the

garnets of one or two localities in Saxony. The paper appeared to be one of exceptional interest and value.

Mr. Barrow was much interested in the Authors' list of minerals developed by contact-metamorphism. The light they had thrown on the origin of cyanite was particularly valuable to geologists working in the Central Highlands, where cyanite schist occurs on a large scale. In one instance a broad belt of this schist follows the outcrop of an igneous gneiss for some miles in such a manner as to suggest contact-metamorphism. The crystals of cyanite show little or no signs of deformation, and if developed by contact-metamorphism seem to point to the conclusion that the igneous rock originally consolidated as a gneiss.

Mr. Marr, in reply, recapitulated the reasons which had caused the Authors to connect granite, felsites, and mica-traps alike with the existence of a deep-seated magma, without asserting which portions of this were first consolidated. The movements in the Pennine Chain to which they had referred were those pre-Carboniferous ones which affected only the Lower Palæozoic rocks. Though the map of dykes exhibited was necessarily diagrammatic, the directions of those dykes which they had not themselves examined were taken from the published maps of the Geological Survey.

He believed that the metamorphism produced by the granite might throw some light upon the changes which had occurred in the rocks of a "regionally metamorphosed" area. The Authors had attempted to show that the Shap-granite intrusion was connected with earth-movements. If such movements had taken place to a greater extent, dynamic metamorphism would doubtless have altered the granite, the dykes, and the various sedimentary and volcanic rocks, but the pre-existing contact-metamorphism might still remain as a factor in the process of regional metamorphism.

Mr. Harker remarked that although new-formed felspar occurs in the most metamorphosed types of all the rocks studied, the minuteness of its grains and their pellucid appearance render it in many cases difficult to distinguish from quartz. Cyanite as a "contact-mineral" had been recorded by Lossen in the Harz.

Mr. Teall and Dr. Hatch also spoke.